Analysis of exposure to vector-borne diseases due to flood duration, for a more complete flood hazard assessment: Llanos de Moxos, Bolivia

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ABSTRACT
Flood hazard is usually assessed based on the hydrodynamic characteristic of flood (water depth and velocity); however, in riverine floodplains, flood events last for several days. In such cases, the long exposure to flood water may cause additional health problems. Nevertheless, usually flood hazard studies do not consider possible hazards due to flood duration. This paper presents a flood hazard assessment methodology for considering flood duration and exposure to vector-borne diseases, and compares flood hazard maps that include and neglect flood duration. Results from a two-dimensional hydrodynamic flood simulation combined with entomological concepts identify any mosquito-breeding pools. Proximity analyses based on mosquito flying range define the areas exposed to mosquitos; hence, to vector-borne diseases. Results were compared with the probability of mosquito occurrence, showing that solely the consideration of flood depth hazard leads to a false flood hazard assessment, under-predicting the flood hazard. Important cities and areas initially considered safe zones may be exposed to health hazards, due to flood duration. Inclusion of flood duration improves flood hazard assessment; hence, improves flood management plans. Maximum flood depth for oviposition (MFDO) and minimum flood duration (MFD) are important variables for defining mosquito-breeding pools. MFDO is the most uncertain variable. Discussion includes advantages in flood hazard assessment and present methodological limitations.

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1. Introduction

Floods are the most common natural disaster and are reported to affect more people than all the other natural hazards combined (Asian Disaster Reduction Center, 2011). Since structural measures to prevent flooding may be impractical due to prohibitive costs, non-structural measures like flood hazard maps are the best instrument for the formulation of land use planning regulations and civil protection plans for emergency management (Semenzin, Bonso, Tommaso, Critto, & Marcomini, 2011); however, development of flood hazard maps is not a simple task due to data requirements and lack of modeling capabilities, especially in developing countries (Furdada, Calderon, & Marques, 2008; Hagen and Lu, 2011). Besides, flood hazard analysis is a multi-dimensional phenomenon and many different maps could be relevant (Bruijn, Klijn, Van De Pas, & Slager, 2015). Even in developed countries, flood hazard maps are outdated and/or lack critical features for supporting land use planning (Stevens & Hanchs, 2014).

A simple approach for developing flood hazard maps is based on past flood observations and inquiries among the population about flood events in a specific area (Furdada et al., 2011; De Risi, Jalayer, De Paola, & Giugni, 2014; Hagen and Lu, 2011). Using this simple methodology, previous studies categorized flood hazard levels in Santiago de Chile according to the recurrence of floods (Krellenberg, Muller, Schwarz, Hofer, & Welz, 2013). Another approach is to define flood hazard levels based on digital elevation models and the distance from flood sources (rivers and lakes) (De Risi, Jalayer, & De Paola, 2015; Tian, Brown, Bao, & Qi, 2015). These approaches were shown to be useful for the assessment of economic damages from flood events (Belmonte, Lopez-Garcia, & Soriano-Garcia, 2011; Cummings, Todhunter, & Rundquist, 2012). A more advanced approach is based on the analysis of the hydrodynamic conditions that could adversely affect people. This approach is becoming popular because the use of two-dimensional (2D) hydrodynamic models allows the simulation of hydrodynamic conditions recorded during flood events (Poretti & Amicis, 2011).

Several studies analyze how the hydrodynamic conditions of flood waters may affect people stability. Some studies suggest that the location of people during a flood event is important for defining the hazard thresholds and propose different flood depth hazard for different locations (Jonkman, Van Gelder, & Vrijling, 2002). Most studies suggest that a combination of depth and velocity (DV) provides a better indicator for analyzing people’s stability: low water depths at high velocities may be more harmful than deeper water depths with low velocity (Abt, Wittler, Taylor, & Love, 1989; Cox, Shand, & Blacka, 2010; Jonkman & Pennin-Roswell, 2008). The relationship between DV and people’s stability was developed based on laboratory tests’ theoretical stability analysis (Cox et al., 2010). Such criteria proved to be useful for analyzing urban flood events when the flood has short duration and high velocities; however, inland riverine flood events in South American floodplains usually last for several days, with very low or even zero flow velocity. In such cases the use of velocity may lead to an underestimation of flood hazard, because hazardous depths would produce a low DV value (Moya Quiroga, Kure, Udo, & Mano, 2016).

Flood hazard criteria based solely on flood depth (such as the Dutch and Japanese criteria) are more suitable for these flood events. Dutch flood hazard criteria divides flood depth into different human height classes: knee deep, hip deep and head deep (Ranzi et al., 2011). The Japanese criterion divides flood depth into different classes considering average-height people from different ages and different flood response alternatives, including the possibility of evacuation to artificial structures (Ministry of Land Infrastructure and Transport (MLIT), 2005).

When analyzing flood events with long duration, it is also important to consider that shallow flood areas may have health effects on people, because of vector and water borne diseases (Kondo, Seo, & Yasuda, 2003). Such a hypothesis is supported by studies that demonstrate that regions affected by long-duration flood events present a higher number of medical visits and hospital admissions than regions not affected by floods (Ohl & Tapsell, 2000). Epidemics of vector-borne diseases like malaria, dengue and yellow fever are common after flood events in the Amazon, in Bolivia (Chavez, 2007). Moreover, in recent years new vector-borne diseases such as from Chikungunya and Zika viruses have propagated in the Americas, becoming endemic because of the favourable climatological conditions (Gutierrez, 2015; Organización Panamericana de la Salud, 2011, 2015) and increasing number of vector-borne diseases (Kraemer et al., 2015). Although some entomological models were developed for analyzing dengue and malaria epidemics (Bombblies, Duchemin, & Eltahir, 2008; Eckhoff, 2011; Ellis, Garcia, Focks, Morrison, & Scott, 2011; Focks, Haile, Daniels, & Mount, 1993), flood hazard studies do not consider possible health hazards due to vector-borne diseases (or flood duration hazard). Neglecting flood duration hazard may result in inadequate flood management plans and hazard communication. Thus, it is important
to propose and to consider methodologies for evaluating flood duration hazard.

The present study aims to:

1) propose a simple methodology for estimating zones exposed to flood duration hazard (vector-borne diseases transmitted by mosquitoes) based on geographic information systems (GIS) techniques for combining hydrodynamic simulations with entomological concepts; and

2) analyze the importance of flood duration by comparing flood hazards maps with and without flood duration hazard.

2. Study area and data

2.1 Study area

In this study, flood hazard assessment was applied to an area 6000 km² located in the “Llanuras de Moxos” (plains of Moxos) in the north-eastern part of Bolivia, between latitudes 12.0ºS and 17.0ºS, and longitudes 62.5ºW and 67.0ºW (Figure 1). The study area includes the cities of Trinidad (most important city in the Bolivian Amazonia), San Javier, the river station Los Puentes and other small communities. Llanuras de Moxos is a vast, seasonally flooded savannah that gets flooded during the high-water period. The study area is

![Figure 1. Study area. (a) Location of Bolivia in South America. (b) Location of the study area in Bolivia. (c) Simulated area with the cities of Trinidad and San Javier. (d) Detail of Suarez Lake and Las Palquitas wetland, south east of Trinidad. (e) Daily discharge of the Mamore river and discharge thresholds of moderate flood and major flood. (Discharge data from Lombardo & Veit, 2014; background image from Bing maps and Google Earth.)](image-url)
flat, with an average slope of 0.014% and shallow rectangular depressions, known as the “rectangular lakes” (Figure 2). The land use is as a tropical savannah composed mainly of grasslands. The study area is drained by the Mamore River, flowing in a south to north direction. A variety of neotectonic activity events caused the formation of several existent shallow rectangular lakes (Lombardo & Veit, 2014). The biggest lake is Suarez Lake, with an area of 5.88 km$^2$ and located some 3.6 km south east of the town of Trinidad. In addition, wetlands such as Las Palquitas can be found south-east of Trinidad. The average discharge of the Mamore River at Trinidad is about 4100 m$^3$/s. During the rainy season, the Mamore River may reach more than 14,000 m$^3$/s; whereas in the dry season, the discharge is about 1500 m$^3$/s. The Flood Observatory (2015) performed a log Pearson III analysis of the Mamore river and differentiates its floods as major floods, when the peak discharge is higher than 11260 m$^3$/s (higher than the 5-year return period); and moderate floods, when the peak discharge is higher than 5541 m$^3$/s (higher than 1.33-year return period).

Llanuras de Moxos are subject to severe inundations, which may reach extents up to 150 000 km$^2$, affecting thousands of people, and lead to human-economic losses equivalent to millions of US dollars (United Nations development program in Bolivia (UNDP), 2011). Because of the low gradient of the plain and the impermeable clay soils, floods last for several days. Such long flood duration originates mosquito breeding pools that result in epidemics of vector-borne diseases such as dengue, malaria and yellow fever (Chavez, 2007). Because of the climatological conditions (humid tropical with a temperature higher than 30°C), every year there are epidemics of vector-borne diseases and the number of cases is increasing (Cespedes, Diez, Tobias, & Tereba, 2015).

3. Methodology

The study analyzed two flood events: one major flood event and one moderate flood event. The major event was defined as a flood event with a peak discharge higher than the 5-year return period, while the moderate flood event was defined as a flood event with a peak discharge higher than the 1.33-year return period (Flood Observatory, 2015). We selected the 2014 flood as the major flood event and the 2002 flood as the moderate flood event. First, we simulated the flood events and assessed the flood hazard; then we analyzed flood duration, in order to assess possible mosquito-breeding pools and areas within the mosquitoes’ flying range. Finally, we compared flood hazard maps based on flood depth with flood hazard maps considering flood duration.

3.1 Flood simulation

Flood events were simulated using the 2D model HEC-RAS, version 5 beta. This model solves either the 2D full Saint Venant equations or the 2D diffusive wave equations. The present study considered the 2D diffusive wave option. We consider that this is a reasonable approach, because for several years the diffusion wave equations approximation have been shown to be adequate to slow, varying phenomena like overland flow with slow-rising flood waves and banks overflow (Leandro, Chen, & Schumann, 2014; Ponce, Li, & Simons, 1978). These are the characteristics of our study area. Moreover, the use of diffusive wave for flood simulation has advantages like faster simulations, fewer parameters required and less physical data required (Moussa & Bocquillon, 2009). The topography of the river and the floodplain was based on the shuttle radar topography mission (SRTM) digital elevation model (DEM). Our study used a grid resolution of 90 m. We used hydrographs of the respective flood events as upstream boundary conditions located at the upstream cells of the Mamore River. Figure 3 shows the respective hydrographs and the discharge thresholds defining a moderate and major flood event. Besides the hydrograph, the upstream boundary condition requires an energy slope (0.0001) for distributing the discharge over the cells. Normal depth was
the downstream boundary condition. The downstream boundary condition was located not only at the downstream extreme of the Mamore River, but also at the borders of the model where the water is supposed to flow. More details about the calibration and performance of the model are described (Moya Quiroga et al., 2016).

3.2 Flood hazard

The study developed two types of flood hazard maps: one flood hazard map based on flood depth and one flood hazard map considering flood duration.

3.2.1 Flood depth hazard

Flood hazard due to flood depth was assessed according to the Japanese criteria (MLIT, 2005). This classifies the possible human damage caused by different flood depths and considers the possible response from people, defining five hazard categories. When flood depth is shallower than 0.50 m, the flood is considered as low hazard; people will not drown and people can walk and evacuate normally. When the flood depth is between 0.50 m to 1.0 m, the flood is considered as medium hazard; flooding may drown children and adult evacuation becomes difficult. When the flood depth is between 1.0 m to 2.0 m, the flood is considered as high hazard; flooding may drown people unless they evacuate to a second floor or to some artificial structure. When flood depth is between 2.0 m and 5.0 m, it is considered as a very high hazard; flooding may drown people unless they evacuate to the roof of their building or to some artificial building with such height. When flood depth is deeper than 5.0 m, it is considered as an extreme hazard; flooding will drown people and may destroy buildings that are up to 5 m tall. Figure 4(a) presents a graphical explanation of the flood depth hazard.

3.2.2 Flood duration hazard

When floods last for several days, epidemic episodes of vector-borne diseases and water-borne diseases are expected to occur. The present flood duration hazard analysis focused on the exposure to vector-borne diseases, because they are the most common health problems related to flooding events in the study area (Chavez, 2007; UNDP, 2011). Previous research shows that the combination of hydrological models to simulate the occurrence of pools (mosquito habitat) with agent-based entomological models provides good estimations of dengue and malaria epidemic dynamics (Bomblyes, 2012; Shaman, Stieglitz, Stark, Blancq, Le, & Cane, 2002). In the present study, a hydrodynamic simulation was used to simulate the occurrence of flood pools. The entomological concepts were then considered, in order to estimate the occurrence of mosquito-breeding pools. Vector-borne diseases in the study area are transmitted by the Aedes and Anopheles mosquitoes (Chavez, 2007; Lardeux, Aliaga, Tejerina, & Torrez, 2013). Mosquito survival and mosquito biting behaviour are important factors that define vector-borne disease transmission dynamics (Ellis et al., 2011). The first factor defining mosquito occurrence and survival is temperature. Mosquitos die when temperatures are lower than 16°C or higher than 40°C (Bomblyes & Eltahir, 2009). The ideal temperature for mosquito survival is between 20°C and 30°C (Maarten, 1997). The present study assumed ideal temperature conditions for mosquito survivability (details in the discussion). The other factor defining mosquito occurrence is the persistence of adequate breeding pools (Shaman et al., 2002). The flood pools must persist long enough to provide a good habitat for mosquito and to allow development from egg to adult mosquito. If mosquitoes oviposit in a...
pool that gets dry before the emergence of adult mosquitoes, that cohort of mosquitoes will die. Mosquito entomological models suggest an egg-to-adult mosquito time threshold between 7 (Shaman et al., 2002) and 10 days (Favier, Degallier, & Dubois, 2002). The present study considered those two values as the minimum flood duration (MFD) for mosquito occurrence. Besides, it is important to consider that flood pools should not be too deep, because oviposition will not occur in pools deeper than a given threshold (Minakawa & Sonye, 2005). When flood pool depth reaches a certain threshold depth, its wave action will either drown mosquito larvae or prevent oviposition (Bomblies, 2012). The threshold depth of this maximum flood depth for oviposition (MFDO) varies with the characteristics of the location. In vegetation-free locations, this threshold depth is limited to few centimeters. In other locations, vegetation may keep calm water conditions at deeper flood depths. By the time this article was written, we had not found any criterion for defining this threshold depth. Thus, the present study assumed possible threshold values based on the vegetation characteristics of the area (assuming that vegetation will help in keeping calm water conditions). The study area is covered by grasslands for Nellore cattle. The most common tropical forage for Nellore cattle is Panicum maximum pasture (Maciel et al., 2013). The maximum height for this grass is between 0.25 m to 0.50 m, because it provides optimal net forage accumulation with a higher leaf-to-stem ratio and delays senescence of the grass (Da Silveira, Cunha, Difante, Pena, Da Silva, & Sbrissia, 2010). The present study considered those two MFDO values.

In summary, the present flood duration hazard criteria depend on two unknown parameters for defining mosquito-breeding pools: MFD and MFDO. Based on the mentioned criteria, this study analyzed the performance of the possible MFD and MFDO values; and considered two MFD values (seven and ten days) and two MFDO values (0.25 and 0.50 m). Besides, it is important to consider that mosquito will fly some distance to feed. Mosquito behavior analysis depends on several factors, such as wind direction, wind speed, number of feeds per day, population and others. Such data is not available. Besides, the present study aims to analyze the areas exposed to mosquitos (not the mosquito dynamics). Thus, a proximity analysis using GIS was performed for defining the areas exposed to mosquito, considering mosquito flying distances. The study used the proximity analysis tool from QGIS. In the present study, a distance of 3500 m was assumed, because the Aedes and Anopheles mosquitoes have an average MFD of 3500 m (Verdonschot & Besse-lotskaya, 2014). Areas located closer than 3.5 km from the mosquito breeding pools were considered as high hazard zones; however, some studies report that under some circumstances, mosquitos may fly up to 10 km (Bogojevic, Merdic, & Bogdanovic, 2011). Thus, areas located closer than 10 km from the mosquito breeding pools were considered as low hazard zones. Figure 4(b) shows the flood duration hazard as a combination of flood depth, flood duration and distance. Table 1 summarizes the data used in the study.

4. Results

Figure 5 shows a comparison between the 2014 flood depth hazard (major flood) and the 2002 flood depth hazard (moderate flood). In both events, the west floodplain is exposed to higher flood depth hazard. The main differences are on the east floodplain,
where the main cities are located. During major flood events, the city of Trinidad is surrounded by medium hazard flood water and San Javier is flooded by flood water categorized as very high hazard flood. On the other side, during moderate flood events, the city of Trinidad does not experience any flood hazard and San Javier experiences moderate flooding. Analyzing the whole 2014 flood event (video annexed from Moya Quiroga et al., 2016), it is possible to define the main overflow points and overflow dates. The first overflow that floods the western floodplain originated at Point A on February 4, 2014. The overflow that triggered the flood event, which threatened San Javier, originated at point B on 5 February 2014. The overflow that triggered the flood event, which threatened Trinidad, originated at point C on 10 February 2014. Thus, it is possible to define threshold discharges: point A and point B begin to overflow when the Mamore river discharge is higher than 5500 m$^3$/s, while point C only begins to overflow when the Mamore river discharge is higher than 9800 m$^3$/s. The peak discharge during the 2002 flood event was 6400 m$^3$/s. Thus, it may be assumed that Trinidad is exposed to flood depth hazard only for flood events with a peak discharge higher than 9800 m$^3$/s.

Figures 6 and 7 show the different flood duration hazard maps according to the different combinations of MFDO and MFD for the 2014 and the 2002 flood events, respectively. Table 2 summarizes the number of potential breeding pool cells for the different thresholds. The definition of breeding pool cells is more sensitive to MFDO than to MFD. The variation in the number of breeding pool cells considering the different MFDO thresholds is twice the variation of the number of breeding pool cells considering the different MFD thresholds.

**Table 1.** Data used in the present study.

| Data                        | Value                          |
|-----------------------------|--------------------------------|
| Major flood                 | 2014 (5-year RP) (Flood Observatory, 2015) |
| Moderate flood              | 2002 (1.33-year RP) (Flood Observatory, 2015) |
| Flood depth hazard          | Japanese criteria (MILT, 2005) |
| MFDO                        | 0.25 m and 0.50 m               |
| MFD                         | 7 days and 10 days              |
| MFDT                        | 3.5 km and 10 km                |
| 2D simulation               | HEC-RAS v. 5 beta (Moya Quiroga et al., 2016) |

MFDO = maximum flood depth for oviposition. MFD = minimum flood duration. MFDT = maximum fly distance threshold. RP = return period.

**Table 2.** Mosquito breeding pool cells (BPC) for different flood events and different flood thresholds of maximum flood depth for oviposition (MFDO) and minimum flood duration (MFD).

| Type of flood | MFDO [m] | MFD [days] | BPC |
|---------------|----------|------------|-----|
| Major flood   | 0.50     | 7          | 9410|
| Major flood   | 0.50     | 10         | 4526|
| Major flood   | 0.25     | 7          | 2153|
| Major flood   | 0.25     | 10         | 800 |
| Moderate flood| 0.50     | 7          | 4466|
| Moderate flood| 0.50     | 10         | 987 |
| Moderate flood| 0.25     | 7          | 582 |
| Moderate flood| 0.25     | 10         | 47  |

**Figure 5.** Flood depth hazard simulated by the present study for (a) a major flood event and (b) a moderate flood event.
5. Discussion

The 2014 flood event shows that when flood duration is not considered, the flood hazard is underestimated. The most important underestimated hazard is in the area of Trinidad. Considering only flood depth hazard, the city of Trinidad is considered as a safe location; however, flood duration criteria shows that Trinidad is exposed to vector-borne diseases. The flood exposure depends on the MFDO value. When 0.50 m is assumed as MFDO, the whole city of Trinidad is categorized as highly exposed to mosquitoes; as it is closer than 3500 m from mosquito breeding pools. On the other hand, when 0.25 m is assumed as MFDO, only the north west of Trinidad is categorized as highly exposed to mosquitoes. This difference is because MFDO affects the number and location of breeding pools. In the case of San Javier, in all the cases the city is within the 10 km range of mosquitoes. There are no breeding pools in San Javier, because the flood depths are deeper than the MFDO. Analyzing the whole study area, the mosquito breeding pools are distributed along the flooded area. There are important clusters of breeding pools located south of Trinidad and some 10 km north of San Javier. When 0.50 m is assumed as MFDO, there are several isolated breeding pools in the flooded area. They are unusual locations, considering that they are surrounded by high water depths. During moderate flood events Trinidad is not exposed to flood duration hazard and San Javier may be exposed to vector borne diseases if a 0.50 m MFDO threshold is selected. The other areas exposed to vector-borne diseases are

Figure 6. Flood duration hazard (areas exposed to mosquitoes) considering different maximum flood depths for oviposition and the minimum flood duration for a major flood event.
located at more than 3.5 km from the cities; thus, flood duration hazard during moderate flood events is minor. This low exposure to vector-borne diseases during the 2002 flood simulation is supported by the fact that the year 2002 is coincident with the lowest number of vector-borne diseases in Bolivia (Ministerio de Salud y Deportes (MSD) de Bolivia, 2012).

The main purpose of flood hazard maps is to support flood risk management and spatial planning. The use of incomplete flood hazard maps neglecting hazard sources and/or underestimating the real hazard may lead to wrong decisions (Scolobig, 2015). The present study shows the importance of considering flood duration in riverine flood hazard analysis. Important urbanized areas not exposed to flood waters may be exposed to flood duration hazards. For instance, in the present study, the city of Trinidad is not affected by flood water and categorized as a safe area; however, Trinidad is categorized as highly exposed to vector-borne diseases. On the other hand, San Javier shows the opposite. The city is highly exposed to flood depths, but has lower exposure to vector-borne diseases.

The present study shows that possible flood management plans are highly dependent on both criteria.

Figure 7. Flood duration hazard (areas exposed to mosquitos) considering different maximum flood depths for oviposition and minimum flood duration for a moderate flood event.
In the case of San Javier, flood depth is critical for flood management plans and should be the priority. In the case of Trinidad, flood management plans should prioritize health effects and mosquito control measurements (flood duration). Thus, it is important to consider both criteria: flood depth hazard and flood duration hazard.

The flood duration hazard is more uncertain than the flood depth hazard, because it depends on the unknown thresholds MFDO and MFD. The mosquito exposure maps were compared with the mosquito occurrence probability map (MOPM) as previously reported (Sinka et al., 2010), shown in Figure 8. The MOPM shows that Trinidad has a higher mosquito probability than San Javier. Besides, the MOPM shows that both the north and the south east of Trinidad have the highest mosquito occurrence probability. The north of Trinidad shows a high mosquito exposure with both MFDO values (0.50 m and 0.25 m). The high mosquito exposure in the south east is coincident with the flood duration hazard when 0.50 m is assumed as the MFDO, but not when 0.25 m is assumed as the MFDO. Thus, the land conditions south east of Trinidad allow for mosquito breeding pools at a deeper MFDO than other locations; this higher MFDO may be because of the presence of water bodies like Suarez Lake and the Palquitas wetlands. According to the MOPM, the north west of San Javier shows the highest mosquito probability. This is coincident with the mosquito exposure maps developed for a major flood event. The mosquito exposure of San Javier during moderate flood events (1.33-year return period) is highly dependent on the MFDO. If 0.50 m is assumed as MFDO, San Javier would have a high exposure to vector-borne diseases. This result would be in contradiction with the MOPM. On the other hand, if 0.25 m is assumed as MFDO, San Javier would have some exposure to vector-borne diseases. Thus, it is suggested to assume 0.25 m as the MFDO for the area around San Javier. The west side of Trinidad also shows medium exposure to vector-borne diseases; however, the flight distance assumed for the medium hazard (10 km) is the maximum distance reported at other locations under some circumstances. Thus, it is possible that the present threshold may overestimate the maximum flight distance. The west floodplain of the Mamore has a low mosquito probability. This low exposure is best represented assuming a MFDO of 0.50 m and a 10-day MFD. This low mosquito probability could also be explained by the fact that this western floodplain has no human population; thus, it may be assumed that mosquitoes will die in such a location because they feed almost exclusively on humans (Kraemer et al., 2015). The results show that flood duration hazard is better analyzed by considering a spatially variable MFDO. Thus,

![Image](https://example.com/image.png)

**Figure 8.** Mosquito occurrence probability. (Based on results from Bogojevic, et al., 2011.)
future research about the MFDO at the study area is suggested, in order to improve the understanding and the simulation of more detailed mosquito dynamics considering an agent-based criterion.

Flood hydrodynamics controls mosquito population dynamics; however, it is not enough to consider only the hydrodynamic conditions that lead to pool areas. MFDO and MFD are important entomological parameters that affect the number and location of mosquito-breeding pools and the mosquito exposure. The present methodology yields to a credible and reasonable estimation of mosquito-breeding pools and areas that are exposed to mosquitoes. The combination of the hydrodynamic conditions and entomological concepts provides a good indicator of breeding pools’ persistence. Besides, the inclusion of flying ranges allows the identification of areas susceptible to mosquito activity during riverine flooding events. Comparing the results from different MFDO and MFD, it may be concluded that the MFDO plays a more important role.

The present methodology can be used to explore the effects of urban development plans on mosquito-breeding pools and mosquito exposure. More detailed simulations for urban environments considering finer resolution topography could be used for a more detailed analysis of mosquito-breeding pools in urban areas. Besides, different environmental management scenarios can also be evaluated. Most common mosquito abatement practices like filling pools in can be evaluated applying a prior modification of the DEM. On the other hand, other practices like using larvicides are more difficult to include in the current methodology. Some possibilities for considering use of larvicides could be to modify the mosquito breeding pool criterion or to assume there are weaker mosquitoes with shorter flying ranges; however, such options require further research.

Other possible limitation of the present methodology concerns its applicability for climate change scenarios. The present study assumed ideal temperature conditions. This is a reasonable assumption, considering the climatological conditions in the study area. Figure 9 shows the daily temperature variation in Trinidad, as reported by the Bolivian meteorological service (SEMANH), and the respective mosquito survival probability according to previously published material (Maarten, 1997). Higher temperature would decrease mosquito survivability (Bomblies, 2012) and may slow their development times (Bomblies & Eltahir, 2009). When temperature is outside the ideal range, the MFD could be changed to a higher value. In cases where the temperature is higher than 40°C or lower than 16°C, it may be assumed that a mosquito dies. The relative humidity in the study area varies between 67% and 83% (Instituto nacional de estadistica Bolivia (INE), 2012); thus, there is no need to apply the survival correction suggested by a previous publication (Yamana & Eltahir, 2013) for humidity stress conditions (when relative humidity is lower than 42%).

In some cases, the water quality may influence mosquito development and their life span; however, it is reasonable to assume that in the present case, the influence of the water quality is negligible. The Mamore river has a good water quality without organic contamination, and a pH between 6.1 and 6.4 (Cholima, Velasco, Rodal, & Zapata, 2014), and it is known that mosquito development is successfully completed in water with a pH ranging between 4 to 11 (Clarck, Flis, & Remold, 2004). The Mamore River has a low salinity, considered among the lowest in the world (Roche & Jauregui, 1998); thus, considering that mosquitoes were reported to reproduce even in brackish waters (Jude et al., 2012), it may be assumed that the water quality of the Mamore River poses no problems for mosquito development.

The flying range in the present study did not consider wind speed, which is an important factor for analyzing mosquito dynamics. This study did not

Figure 9. Daily temperature and mosquito survival probability in the study area.
consider wind speed because of data limitations. The only wind speed data of the study area provides monthly average wind conditions (SENAMHI Bolivia, 2001; SIMBIOSIS, 2013). The average wind conditions in Trinidad during the month of February have wind directions N and WNW with speeds between 5 knots (2.5 m/s) and 7 knots (3.6 m/s). Such wind speeds are faster than the average mosquito flying speed of 1.0 m/s (Becker et al., 2010). Thus, it is reasonable to assume that the present study overestimated the flying range of mosquitoes in locations that are not within the N–WNW of the breeding pools. During major flood events Trinidad is located N–WNW from breeding pools. This confirms that the city of Trinidad is highly exposed to vector borne diseases. Nevertheless, the mentioned wind speed and wind direction values are monthly ones; the only data available. Wind conditions with shorter temporal scale (daily or hourly) would provide a better analysis.

It is important to note that mosquito population dynamics is sensitive to weather (rainfall) and human activities. Small water containers and discarded water tires may become breeding pools after rainfall events (Barrera, Amador, & MacKay, 2011). However, such analysis would require a detailed high resolution topography including micro-topography. The present study neglected such analysis because of the size and scale of the study. Future studies may perform a more detailed analysis of the areas identified as potential breeding pools, considering micro-topography; they may also improve the estimation of breeding pools by including the processes of rainfall, infiltration and evaporation.

6. Conclusions

The flood hazard in the Bolivian Amazonia was assessed considering flood depth and flood duration. Flood depth hazard was assessed based on Japanese criteria; and a new methodology for flood duration hazard was proposed, considering the exposure to vector-borne diseases. Exposure to vector-borne diseases was assessed using GIS techniques for combining results from a 2D simulation with entomological concepts about mosquito-breeding pools and mosquito flying range.

This study shows that it is important to consider both flood depth and flood duration criteria for flood hazard assessment and for planning flood management alternatives. In some cases, an area may be considered a hazard area considering one criterion, but it may be considered as a safe area considering other criteria. In other cases, the areas may be categorized as hazard areas considering both criteria.

The most important cases in this case study, where the use of only one flood criterion may lead to erroneous hazard assessment, are the cities of Trinidad and San Javier. Trinidad may be considered as a safe area considering the flood depth criteria; however, when flood duration is considered, the city is very close to several mosquito-breeding pools and Trinidad is considered as a hazard area. San Javier is highly exposed to flood depth, but it is far from mosquito breeding pools. Nevertheless, San Javier may be considered as an area exposed to mosquitoes, because of the mosquito flying range.

MFDO and MFD are important entomological variables for identifying mosquito-breeding pools and areas exposed to mosquitoes. Assuming a MFDO value of 10 days is a reasonable value that leads to good results. MFDO is the most sensitive variable, with the highest uncertainty. MFDO depends on the land characteristics and the micro-topography. The areas around Trinidad are best analyzed by considering a MFDO of 0.50 m, while other areas are best analyzed by considering lower MFDO values. Although the values assumed in the present study provided good qualitative results, we suggest performing further research considering a spatially variable MFDO.

The present study proposed the combination of results from a hydrodynamic simulation and entomological concepts for analyzing locations where pool persistence yields to conditions for mosquito-breeding pools. Besides, the inclusion of flying ranges allows identification of areas that could be susceptible to mosquito. Nevertheless, the present study was applied to one specific case where climatological conditions (temperature and relative humidity) are ideal for mosquito survival. Thus, additional research considering non-ideal climatological conditions is suggested.

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