Climate change and debris flow: hazards maps in Matucana village Peru under IPCC scenarios

JUAN W. CABRERA CABRERA & LEONARDO F. CASTILLO NAVARRO
Facultad de Ingeniería Civil, Universidad Nacional de Ingeniería, Lima 25, Perú
juancabrera@uni.edu.pe

Abstract In this document, the possible effects of climate change on flood and vulnerability of Matucana Village in the next 90 years are discussed based on existing data and projected changes in precipitation until 2099. This village is located in the lowest zone of Pahuia ravine and continuously suffers the effects of floods and debris flows. The analysis was made using changes projected by the ECHAM4/OYPY3, GFDL R30, HadCM3 and NCAR DOE PCM models because these models have the highest spatial resolution. The interval defined by these models was considered, such as the variability interval. The analysis considered three scenarios: mean scenario, with mean changes projected; and minimal and maximum scenarios, defined by the lowest and highest changes projected. The final results suggested no significant increment in magnitude or affected area by debris flow in the next 90 years under the A1FI emission scenario.

Key words AOGCM; climate change; flood; hazard map; IPCC scenarios; debris flow; Peru

INTRODUCTION
Matucana village is located on the left bank of the Rimac River around 2375 m a.s.l in the Western Chain of the Central Peruvian Andes, where two tributary streams’ alluvial fans impact on urban areas. On the left bank is Chucumayo ravine and on the right bank is Pahuia ravine. Both streams have an accelerating geodynamic activity, i.e. debris flows becoming more frequent and with higher volumes and intensities through time.

Pahuia is a high slope basin with much accumulated material in its bed, with large increases in flow due to runoff causing landslides and collapses. This ravine does not act directly on the urban area, but its effects are directly on it because the debris flow material falls directly into the Rimac River producing floods on Matucana urban area, which is at a lower level than the river.

Climate change suggests a possible increment in precipitation and consequently, an increment in debris flow occurrence and increment in magnitude and intensity. This situation determines the necessity of studying the possible effects of climate change on the magnitude and recognition of the possible hazard zones and re-organize and prepare mitigation plans.

STUDY METHODS
Data
Analysis of extreme events requires maximum precipitation time series. CESEL (2004) realized this in their analysis by fitting a Gumbel distribution. Parameters of this probabilistic distribution function were taken from the Estudio hidrológico de la quebrada Collana (CESEL, 2004).

Arithmetic mean values for the period 2010–2099 were estimated by using projected percentage changes according to ECHAM4, NCAR PCM and HADCM3 models and the A1FI emission scenario. These models were selected because they have the highest spatial resolution; GFDL R30 model was discarded because it did not include the mentioned emission scenario. Projected changes are for the period 1961–1990 and are available in Ruostenoja et al. (2003).

Topography and other main stream and basin characteristics were estimated from National Maps from the Instituto Geográfico Nacional (IGN): the main channel slope was estimated to be 0.39 m/m and lag time as 1.2 h.

To estimate infiltration volume, analysis from Castillo (2006) was taken. According to this work, the Pahuia ravine shows a characteristic such as hydrologic soil type “B” and 79 could be assigned as the weighted curve number.
METHODOLOGY

The IPCC projected changes of precipitation (\(\Delta P\)) are the percentage changes related to the period 1961–1990. For this analysis only ECHAM4, NCAR PCM and HADCM3 models were considered. Table 1 shows the percentage variation for the December–February period for 2010–2099 according to these models. Months between March to November were not considered because they form the dry season in the Southern Hemisphere.

Table 1 Percentage variation for December–February period according to different climatological models and time periods. Emission scenario A1FI. Region 11.

<table>
<thead>
<tr>
<th>Time</th>
<th>2010–2039</th>
<th>2040–2069</th>
<th>2070–2099</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECHAM4</td>
<td>2.02</td>
<td>2.63</td>
<td>8.80</td>
</tr>
<tr>
<td>NCAR PCM</td>
<td>-0.86</td>
<td>4.93</td>
<td>6.77</td>
</tr>
<tr>
<td>HADCM3</td>
<td>-1.41</td>
<td>-6.50</td>
<td>-14.28</td>
</tr>
</tbody>
</table>

Source: from Ruostenoja et al. (2003).

Historical data have a standard deviation \(s = 24.4\) and arithmetic mean value \(\mu = 13.9\). Considering that all the time series will be affected by a projected change, we can assume that all data will be displaced, but the scatter (standard deviation) will be maintained. Arithmetic mean value will be affected by this projected change by:

\[
\mu_{\text{proy}} = (1 + \Delta P) \mu
\]

where \(\Delta P\) is projected changes of precipitation (%) to the interval “n”; \(\mu\) is historical mean value, and \(\mu_{\text{proy}}\) is projected mean value. These could be: 2010–2039, 2040–2069 or 2070–2099.

This assumption is acceptable because this region is climatologically homogeneous (Rau et al., 2011). These two new parameters define a Gumbel probability distribution function for every period in the analysis. Then we can estimate the new maximum precipitation for \(Tr = 100\) years using the following expression:

\[
P_{\text{proy}} = \mu_{\text{proy}} + K * S
\]

where \(K\) is the “frequency factor” and depends only on the time of return:

\[
K = -\frac{\sqrt{6}}{\pi} \left(0.5772 + \ln[\ln(Tr/(Tr - 1))]\right)
\]

This maximum precipitation and main stream parameters, slope, concentration time, lag time, curve number) were input to HEC-HMS software to evaluate peak flows.

Finally, the hydrograph from HEC-HMS, maximum precipitation and topography was input to FLO2D software to simulate correspondent debris flow. Other basin characteristics such as Manning’s roughness, viscosity and yield stress, were taken from Castillo (2011). The output showed affected areas, maximum depth and the water and solid volumes.

RESULTS AND DISCUSSION

Precipitation probabilistic distribution

The Gumbel distribution was assumed and fitted to historical data. Considering that this region is climatologically homogeneous (Rau, 2011), the standard deviation will maintain the same value, but new mean values were estimated for every one of the three time periods in evaluation; in this way, nine new distributions are created, three of them distributed to minimal change projections (minimal scenarios), three to the mean change projections (mean scenarios) and finally, three to maximum change projections (maximum scenarios). Also, the precipitation for the 100 year return period was estimated for every distribution. A summary of these values is shown in Table 2.

As the minimal scenarios showed a reduction in precipitation, these three scenarios were discarded. The remaining scenarios were analysed to estimate the corresponding hydrographs and
Table 2 Mean values and maximum precipitation to Tr = 100 years to different scenarios and different time periods.

<table>
<thead>
<tr>
<th></th>
<th>2010–2039</th>
<th>2040–2069</th>
<th>2070–2099</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ (mm)</td>
<td>P100 (mm)</td>
<td>µ (mm)</td>
</tr>
<tr>
<td>Maximum projected change</td>
<td>14.05</td>
<td>90.68</td>
<td>14.13</td>
</tr>
<tr>
<td>Mean projected change</td>
<td>13.76</td>
<td>90.39</td>
<td>13.82</td>
</tr>
<tr>
<td>Minimal projected change</td>
<td>13.57</td>
<td>90.21</td>
<td>12.87</td>
</tr>
</tbody>
</table>

Table 3 Peak flows for every scenario to be analysed.

<table>
<thead>
<tr>
<th></th>
<th>Peak flow (m^3/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010–2039</td>
</tr>
<tr>
<td>Maximum projected change</td>
<td>34.8</td>
</tr>
<tr>
<td>Mean projected change</td>
<td>34.6</td>
</tr>
</tbody>
</table>

peak flows (see Table 3). Results showed similar values for the mean scenarios and only one simulation was considered for this group of scenarios. In a similar way, the maximum scenarios have two similar values and this was also considered as one.

According to this result, only three scenarios were analysed: one mean scenario (2010–2099) and two maximum scenarios (2010–2069 and 2070–2099). The similarity in peak flows and maximum precipitations (P100) suggested that simulations would have similar output in debris flow volumes, depth and inundated area. These values are also similar for the reference period, as shown in Fig. 1.

Debris flow simulation

Simulation of the debris flow was made by applying FLO2D software and considering 22% to 35% sediment concentration (Castillo, 2006). Results show similar output for the different scenarios with respect to the maximum inundated area; this means that the effect of climate change will not increase maximum inundated areas in an important way, as seen in Table 4.

A comparison with historical data analysis is summarized in Table 5. There is a consistent similarity between the different scenarios and consequently the plots are similar too (see Fig. 2).

Figure 2 shows the maximum depth on the analysed surface for different scenarios. These plots show similar inundated areas and similar maximum depth along the area and are coherent with output tables and suggest that the hazard maps do not vary in a significant way.
Table 4 summarizes the water and sediment volumes and maximum inundated area for every scenario.

<table>
<thead>
<tr>
<th></th>
<th>Mean scenarios 2010–2099</th>
<th>Maximum scenarios 2010–2069</th>
<th>Maximum scenarios 2070–2099</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water (m³)</td>
<td>Bulked w/sediment (m³)</td>
<td>Water (m³)</td>
</tr>
<tr>
<td>Inflow hydrograph</td>
<td>656 028</td>
<td>971 190</td>
<td>527 730</td>
</tr>
<tr>
<td>Floodplain storage</td>
<td>3545</td>
<td>4663</td>
<td>11937</td>
</tr>
<tr>
<td>Floodplain outflow</td>
<td>652 526</td>
<td>966 554</td>
<td>515 836</td>
</tr>
<tr>
<td>Maximum inundated area</td>
<td>33 600</td>
<td></td>
<td>33 536</td>
</tr>
</tbody>
</table>

Table 5 Comparison between expected debris flow to historical data analysis and projected data analysis.

<table>
<thead>
<tr>
<th></th>
<th>Peak flow (m³/s)</th>
<th>Maximum precipitation (mm)</th>
<th>Maximum inundated area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical data</td>
<td>34.3</td>
<td>90.0</td>
<td>33 492</td>
</tr>
<tr>
<td>Mean scenario 2010–2099</td>
<td>34.6</td>
<td>90.4</td>
<td>33 600</td>
</tr>
<tr>
<td>Maximum scenario 2010–2069</td>
<td>34.8</td>
<td>90.7</td>
<td>33 536</td>
</tr>
<tr>
<td>Maximum scenario 2070–2099</td>
<td>35.5</td>
<td>91.6</td>
<td>33 728</td>
</tr>
</tbody>
</table>

Fig. 2 Maximum depth of debris flow. Left, mean scenario 2010–2099. Middle, maximum scenario 2010–2069. Right, maximum scenario 2070–2099. Emission scenario A1FI. Region 11.
CONCLUSIONS

This climate change analysis did not produce an increment in the magnitude of debris flow in the results produced. This means that climate change will not have a significant effect on this basin. However, a downscaling process is recommended to verify these results.

This methodology could be applied in a similar way to other basins to evaluate risk and prepare prevention and mitigation plans for vulnerable regions.

REFERENCES


