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# Assessing the impact of early warning and evacuation on human losses during the 2021 Ahr Valley flood in Germany using agent-based modelling

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## S1 – Fraction of evacuation mode choice

The evacuation mode statistics significantly impact the estimated fatalities across all scenarios and when compared individually ($p < 0.001$). When 100 % of the population evacuates on foot, the median number of fatalities is 229, with an interquartile range of 210–245. In contrast, if the entire population evacuates by vehicles, the median number of fatalities decreases to 133, with an interquartile range of 124-142. These differences affect only fatalities during the evacuation, with extreme median values ranging from 38 to 124 (Fig. S1 and Table S2).

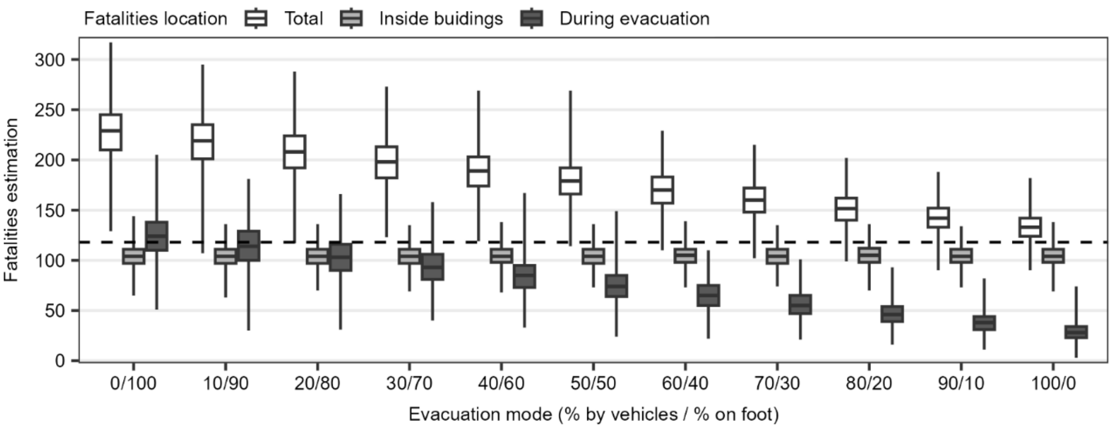


**Figure S1: 2021 Ahr Valley flood estimated fatalities and their location for several fractions of evacuation mode.**

**Table S1: 2021 Ahr Valley flood estimated fatalities statistics for several fractions of evacuation mode.**

| Evacuation mode (% by vehicles / % on foot) | Fatalities estimation | | | | | | | Fraction of indoor fatalities (%) |
|---|---|---|---|---|---|---|---|---|
| | Median | First quartile | Third quartile | Minimum | Maximum | Median inside structures | Median during evacuation | |
| 0/100 | 229 | 210 | 245 | 129 | 317 | 104 | 124 | 45.4 |
| 10/90 | 219 | 201 | 235 | 107 | 295 | 104 | 114 | 47.5 |
| 20/80 | 208 | 192 | 224 | 117 | 288 | 104 | 103 | 50.0 |
| 30/70 | 198 | 182 | 213 | 123 | 273 | 104 | 93 | 52.5 |
| 40/60 | 189 | 174 | 203 | 119 | 269 | 104 | 85 | 55.0 |
| 50/50 | 179 | 166 | 192 | 114 | 269 | 104 | 74 | 58.1 |
| 60/40 | 170 | 157 | 183 | 110 | 229 | 105 | 65 | 61.8 |
| 70/30 | 160 | 148 | 172 | 102 | 215 | 104 | 55 | 65.0 |
| 80/20 | 151.5 | 140 | 162 | 99 | 202 | 105 | 46 | 69.3 |
| 90/10 | 142 | 133 | 152 | 90 | 188 | 104 | 38 | 73.2 |
| 100/0 | 133 | 124 | 142 | 90 | 182 | 104 | 28 | 78.2 |

Although the evacuation mode of 100 % of the population evacuating by vehicles results in a fatality count closest to the actual number (118), the scenario where 80 % evacuate by vehicles and 20 % on foot most matches the proportion of indoor fatalities. This scenario shows a fraction of indoor fatalities at 69.3 %, compared to 68.5 % in the actual event.

**S2 – Alternative warning and evacuation scenarios**

The principal factors affecting the dissemination of the first warning include the number of channels, their technologies, frequency, and the time of day (Sorensen and Mileti, 2015a). Factors influencing most mobilisation times include, in addition to the warning content and perception of personal impacts, environmental cues and impact intensity (Sorensen and Mileti, 2015b). Theorical models are proposed to represent each of these processes based on an extensive database of historical cases involving various hazard sources and previous studies.

In order to estimate the population warned within a specific minute time step ($P_{warned_t}$), the Rayleigh distribution can be employed in conjunction with a specific rate of unofficial means of warning (Equation S1). This model is influenced by two key coefficients: $B_t$ and $C_t$. The coefficient $B_t$ represents the effectiveness of the broadcast channels utilised and serves as the shape parameter of the Rayleigh distribution. Conversely, $C_t$ indicates the efficiency of non-official broadcast means at time step t. Low values of $B_t$ correspond to more efficient broadcast channels, whereas higher values of $C_t$ correlate with an increased rate of the population being warned through informal means. (Sorensen and Mileti, 2015a). For mobilisation, the cumulative probability of being mobilised at minute time t ($P_{mobilised_t}$) is described by Equation S2. This probability depends on the mobilisation speed coefficient ($a_m$) and the median time for individuals to initiate mobilisation ($b_m$). As $a_m$ decreases from a value of 2, the response time accelerates. Conversely, when $a_m$ increases, the response time decelerates. Additionally, higher values of $b_m$ indicate a longer duration to complete the initiation of protective action (Sorensen and Mileti, 2015b).

$$P_{warned_t} = P_{warned_{t-1}} + \left(\frac{t}{B_t^2} e^{-\frac{t^2}{2B_t^2}}\right) + \left(1 - P_{warned_{t-1}}\right) * \left(P_{warned_{t-1}} * C_t\right) \quad \text{(S1)}$$

$$P_{mobilised_t} = 1 - e^{(-(t^2)/a_m b_m{}^2)} \quad \text{(S2)}$$

A specific selection of these cases is utilised to define the proposed curves and their uncertainty bounds in LifeSim. There are ten recommended curves (five for each period of the day) for warning diffusion in LifeSim, derived from six historical cases, including chemical spills, hazardous material flow, volcanic eruptions, and flash floods. Additionally, nine mobilisation curves are combined with levels of perception and preparedness, based on evaluations of three cases involving chemical and hazardous material accidents (Sorensen and Mileti, 2015a, b; USACE, 2020). Table S2 presents the utilised curves, their respective coefficients, and mobilisation rates for each scenario.

**Table S2: First approach of alternative scenarios of early warning and evacuation. Warning diffusion and mobilisation bounds with their coefficients and rates for various scenarios: A1.1 (optimal scenario), A1.2 (intermediate scenario), A1.3 (suboptimal scenario), A1.4 (suboptimal with empirical warning diffusion curve), and A1.5 (suboptimal with empirical mobilisation curve).**

| Alternative scenario | Bounds | Warning diffusion | | | Mobilisation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Curve | $B_t$ | $C_t$ | Curve | $a_m$ | $b_m$ | Maximum mobilisation rate | | |
| | | | | | | | | 8 hours | 24 hours | 72 hours |
| A1.1 | Upper | Fast | 5.0 | 0.100 | Preparedness good perception likely | 1.00 | 25.0 | 100.0 | 100.0 | 100.0 |
| | Most likely | | 9.5 | 0.098 | | 1.37 | 64.0 | 88.8 | 95.7 | 98.6 |
| | Lower | | 51.5 | 0.081 | | 1.80 | 114.0 | 77.1 | 91.1 | 97.2 |
| A1.2 | Upper | Moderate | 58.0 | 0.080 | Preparedness poor perception likely | 1.35 | 61.8 | 81.5 | 95.0 | 98.5 |
| | Most likely | | 100.0 | 0.060 | | 1.79 | 111.8 | 74.3 | 90.0 | 95.0 |
| | Lower | | 142.0 | 0.043 | | 2.20 | 161.9 | 67.1 | 85.0 | 92.0 |
| A1.3 | Upper | Slow | 103.0 | 0.060 | Preparedness poor perception unlikely | 1.35 | 61.8 | 65.9 | 88.7 | 92.8 |
| | Most likely | | 145.0 | 0.042 | | 1.79 | 111.8 | 57.0 | 84.2 | 90.0 |
| | Lower | | 150.0 | 0.040 | | 2.20 | 161.9 | 48.0 | 79.8 | 87.2 |
| A1.4 | Upper | Empirical | | | Preparedness poor perception unlikely | 1.35 | 61.8 | 65.9 | 88.7 | 92.8 |
| | Most likely | | | | | 1.79 | 111.8 | 57.0 | 84.2 | 90.0 |
| | Lower | | | | | 2.20 | 161.9 | 48.0 | 79.8 | 87.2 |
| A1.5 | Upper | Slow | 103.0 | 0.060 | Empirical | | | | | |
| | Most likely | | 145.0 | 0.042 | | | | | | |
| | Lower | | 150.0 | 0.040 | | | | | | |

## S3 – Life loss model convergence

Figure S2 illustrates the estimated fatalities mean, standard deviation, skewness, and kurtosis over model iterations for the reconstruction scenario and the first approach of alternative scenarios. The results indicate that 2,000 iterations are sufficient for the convergence of these statistics.

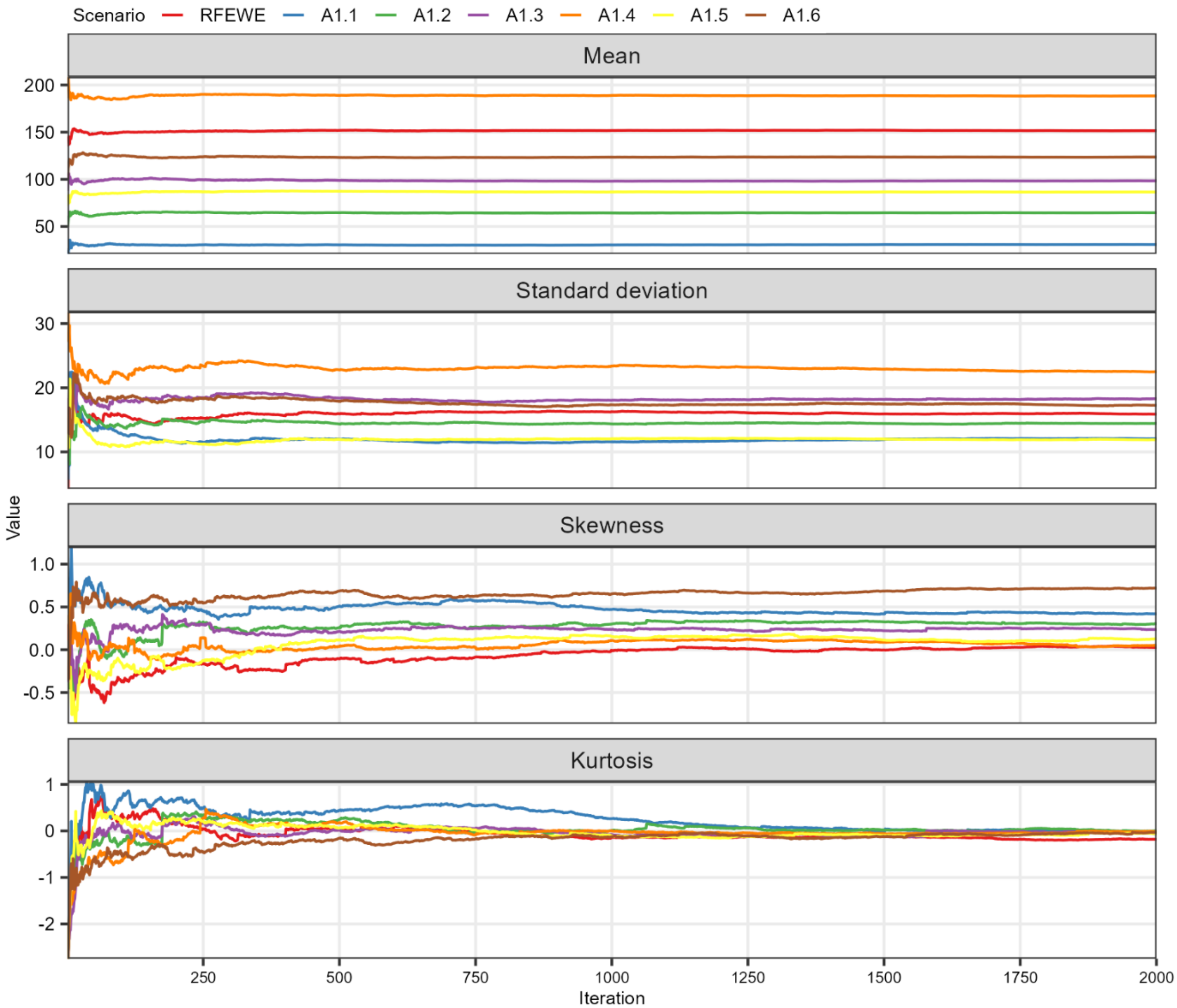


**Figure S2: Estimated fatalities Mean, standard deviation, skewness, and kurtosis trace for reconstructed scenario of the 2021 flood and for the alternative early warning and evacuation scenarios, which focus on evaluating the warning diffusion and mobilisation curves: RFEWE (reconstructed scenario of the 2021 flood), A1.1 (optimal scenario), A1.2 (intermediate scenario), A1.3 (suboptimal scenario), A1.4 (suboptimal with empirical warning diffusion curve), and A1.5 (suboptimal with empirical mobilisation curve).**

**References**

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