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# Evaluation of Flash Flood Vulnerability Scenarios in a Population Growing Mediterranean City: Palma (Balearic Islands, Spain)

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**ABSTRACT:**
Palma's urban continuum, the capital city of the Balearic Islands (Spain), increased 19% its population from 2002 to 2022, achieving ca. 450,000 inhabitants. In terms of urbanisation, between 2005 and 2014 artificial surfaces increased by 7.6% in the urban continuum, and within the flood prone area would be of 10.5%, partially enforced by the population growth. This work aims to assess the potential urbanisation growth during the next eight decades applying land change simulations. Along these new urban spaces, the estimated population growth was distributed, and the results were intersected with the current flood-prone cartography to assess the increase in urbanisation and population over flood prone areas.
The results demonstrated an increase in inhabitants (101.8%) and artificial surfaces (8.6%) exposed to flash floods, sharpening the current vulnerable situation of the city. Achieving 245,112 inhabitants and 3.271 hectares within the flood prone area by 2104. These results may be considered by city planners to avoid the urbanisation over these threatened areas, as well as for the improvement of current emergency management plans. Furthermore, flood-prone areas must be re-estimated due to shorter return periods from increased rainfall intensity, a key consequence of climate change.

*Key Words: Flash floods; natural hazards; vulnerability; GIS.*

## 1. Introduction

Flash floods are a natural phenomenon which can cause heavy impacts on urban environments due to their dragging capacity and flow velocity. In addition, built-up areas contribute to increase the effectiveness of floodings, due to the imperviousness of these spaces, and the alteration of water flows. In fact, floods are one of the natural hazards with higher cost for nowadays societies, both economically and personally, since they are the cause of 40% of all global losses related with natural hazards since 1980 (Papagiannaki et al., 2022). In addition, urban spaces are continually growing, also over flood-prone areas, as well as world's population, and according to this tendency, by 2050 is expected to 68% of world's population to live in cities (United Nations, 2018). This urban and demographic growing binomial is increasing the exposure of people and their goods to floods' damage, generating more vulnerable societies, since the role of anthropogenic interventions on the

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environment may significantly influence flood generation, especially the urbanisation process.
Regarding the climatic side of the problem, extreme precipitation events are becoming more common during the last decades and developing more short but intense precipitation events (Ban et al., 2015). These trends, combined with the urban growth led to making 'impossible' events to happen (Montanari et al., 2024).
Therefore, the aim of this work is to analyse the potential growth in urbanised areas for the next 80-years scenario (i.e. 2032-2050-2086-2104) applying an open-source software for land use change simulations. Secondary, based on the new predicted artificial surfaces, estimations of future population are used to distribute the new population among these new potential urban spaces, to finally evaluate the potential future artificial surface and population exposed to the current flood prone areas.

## 2. Study area

The Balearic Islands, located at the western Mediterranean Sea and at the east of the Iberian Peninsula, emerged during the Alpine Orogeny. Mallorca is the main island of the archipelago, and the 7th in the Mediterranean, with a surface of 3,640 sq km. The island is divided into two main Alpine Mountain ranges, and three Upper Cenozoic basins. At the foothills of the Tramuntana range, the main range in the island, and draining to the south-west, Palma's basin is a subsided depression draining 533 sq km (Petrus et al., 2018) filled by alluvial deposits, and divided into 12 sub-catchments (Fig. 1). Within these 12 sub-catchments, 1,217 hectares of flood prone areas (FPA, from now on) were identified by the Spanish Ministry for the Ecological Transition and Demographic Challenge (MITECO, from now on), and the regional General Directorate of Water Resources.
From these, En Barberà (38.6 sq km) and Gros (205.5 sq km) rivers catchments are the two with a higher risk (Moragues et al., 2025) and, they are included in the Spanish Flood Area Cartography as Areas with Potential Significant Flood Risk (APSFR, from now on), derived from Directive 2007/60/EC on the Assessment and Management of Flood Risks. Along Palma's Basin, 1,217 ha of PFA affect the municipalities of Palma, which is the capital city of the region, and Marratxí, which in the last decades grew due to the conurbation process of Palma consolidated during the 1980s. In fact, Palma's conurbation widely grew since the second half of the 20th century. The population of Palma was 136,000 inhabitants in 1950, and it increased to approximately 300,000 inhabitants by 1991. By the end of the 20th century, the population in Palma was 319,181 inhabitants, and in the urban continuum of Palma and Marratxí was over 350,000 inhabitants, overtopping the threshold of 450,000 in 2019. On its side, Ruiz-Pérez et al. (2023), evaluated the urban development within the APSFR in the aforementioned catchments. The built-up area increased from 2,206 hectares within the 500-years return period, to 24,748 ha in 2021, which supposes an eleven-fold change.

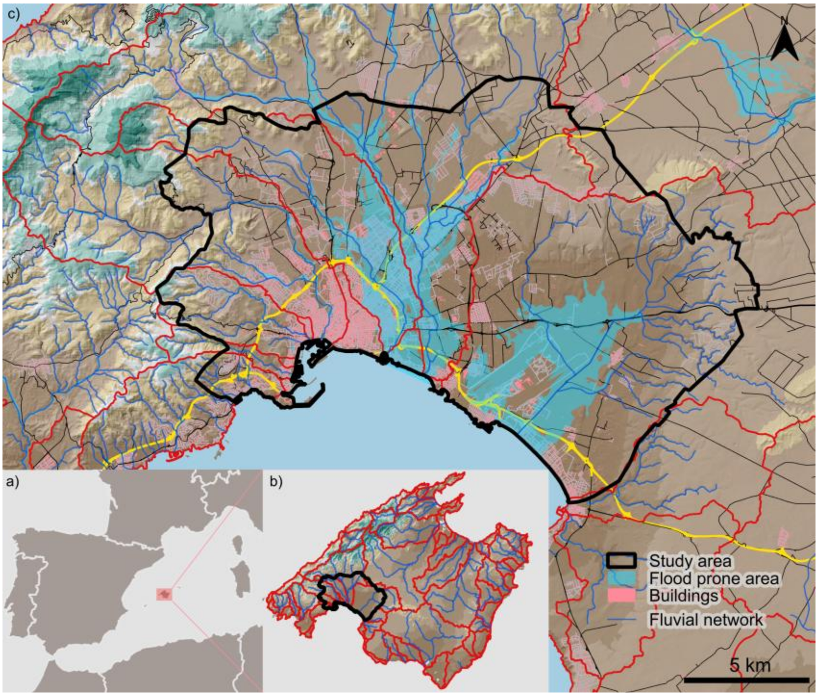


***Figure 1:*** *a) Location of Mallorca in the western Mediterranean Sea. b) Location of Palma basin in Mallorca Island. c) Buildings and constructions in municipalities of Palma and Marratxí. Delimitation of the FPA.*

## 3. Data collection

To perform the land use change simulation, the following data were used:

- Land use and land cover: The Spanish Land Cover Information System (SIOSE, from the Spanish acronym) is a countrywide project, following INSPIRE principles and updated periodically. From this spatial database, the first level of land cover (equivalent to Label 1 from Corine Land Cover) was used, which is classified into: Artificial; Farmland; Natural or semi-natural surfaces and barren land; Wet zones, and Water bodies. The selected datasets were the one from 2005, and from 2014. This is because, from the available datasets (i.e. 2005, 2009, 2011, 2014, and 2017) it captures the period when the higher urbanisation process took place, the reference scale is the same (1:25,000), and a consistency in data was appreciated.
- Slope: The changes in elevations, mountains and hills are one of the main limiting factors for artificial development, contrary to flat areas, which facilitate it. These makes the slope an essential constraint or trigger in urban development (Baig et al., 2022).
- Streets and roads: The communication network formed by streets and roads is an essential trigger for artificial development, since they are axes of infrastructural development (Niehoff et al., 2002), acting as a key driving force (Muhammad et al., 2022). Hence, a raster representing the Euclidean distance to roads is one of the most common spatial parameters used in land cover predictions (Baig et al., 2022; Kamaraj & Rangarajan, 2022).

- River network: Rivers can act as physical limitation conditions, since the channels usually follow the same path (with small dynamic changes), but also, the presence of floodplains of Mediterranean ephemeral streams are a common space for growing up since the last decades (Moragues et al., 2025). To input this condition into the model, Euclidian distance raster was used (Fang et al., 2022; Kamaraj & Rangarajan, 2022).
- Buildings: The presence of buildings favour the development of new urban regions next to the existing ones thus, increasing existing urban nucleus. This principle follows the regional planning directives of new urbanised spaces.

## 4. Methodology

All the aforementioned data: the two land cover maps, and the four conditioning factors were rasterised and snapped into a 2x2 m spatial resolution raster, using QGIS v3.40.6. To calculate land cover changes and potential scenarios, MOLUSCE v.4.2.1 (NextGIS, 2024) plug-in for QGIS was applied. To reckon the potential changes, harbours and new artificial surfaces over the sea were removed with the aim of focusing on potential residential areas, and because of some discrepancies in the original data.

On the one hand, Cellular Automata Artificial Neural Network (CA-ANN) method was used to train a model capable of predicting land cover changes. This model was trained with a neighbourhood value of 1 pixel (meaning a 3x3 pixel window), a learning rate of 0.001, a maximum number of iterations of 750, 3 hidden layers, and a momentum of 0.01. 10,000 samples were randomly defined, and an overall Δ accuracy of -0.0002 was obtained. Moreover, minimum validation error was 0.036, and current validation Kappa was 0.84, which supposed a quite good accuracy result.

From this trained model, various CA simulations were run with 2; 4; 6; 8; and 10 iterations, being each iteration equal to the time interval of the input land cover maps (i.e. 9 years). Therefore, land covers were simulated for 2032, 2050, 2068, 2086 and 2104.

On the other hand, population growth was calculated based on an exponential decay function, as a reliable and efficient model for estimating future population, assuming a constant growth rate for the period 2005 - 2014.

The rate of growth was calculated applying the compound annual growth rate (CAGR, from now on) formula (eq. 1) (Zuniga et al., 2012), and the result was used as input for the exponential decay function (eq. 2) to calculate future population for the 5 future scenarios when land cover simulations were obtained.

$$CAGR = \left(\frac{EV}{BV}\right)^{\frac{1}{n}} - 1 * 100 \qquad \text{(eq.1)}$$

Where $EV$ is the population at the end of the period, $BV$ is the population at the beginning of the time period, and $n$ is the number of years.

$$P(t) = P_0 * e^{r * t} \qquad \text{(eq. 2)}$$

Where $P$ is the population, $r$ is the rate of growth, and $t$ is the number of years to predict.

Finally, a direct distribution was used to distribute population among the artificial surfaces (i.e. people per pixel), knowing all the limitations it implies, since different urban morphologies lead to different population densities, and not all artificial surfaces have as residential purpose. Despite these limitations, population was equally distributed assuming a constant population density along all the artificial surfaces for each future scenario.

## 5. Results and discussion

Between 2005 and 2014, artificial surfaces increased from 37.1% to 44.7% (total of 7.6%, or 1,887 ha), whereas agricultural and semi-natural surfaces decreased by 4.8% and 2.8%, respectively. From this evolution to artificial surfaces, there were 13.7% of agricultural surfaces artificialised, whereas for semi-natural areas it was nearly 11%. On its side, 6.1% of wetlands were also urbanised. Within the flood prone area, artificial surfaces increased by 10.5% (510 ha).

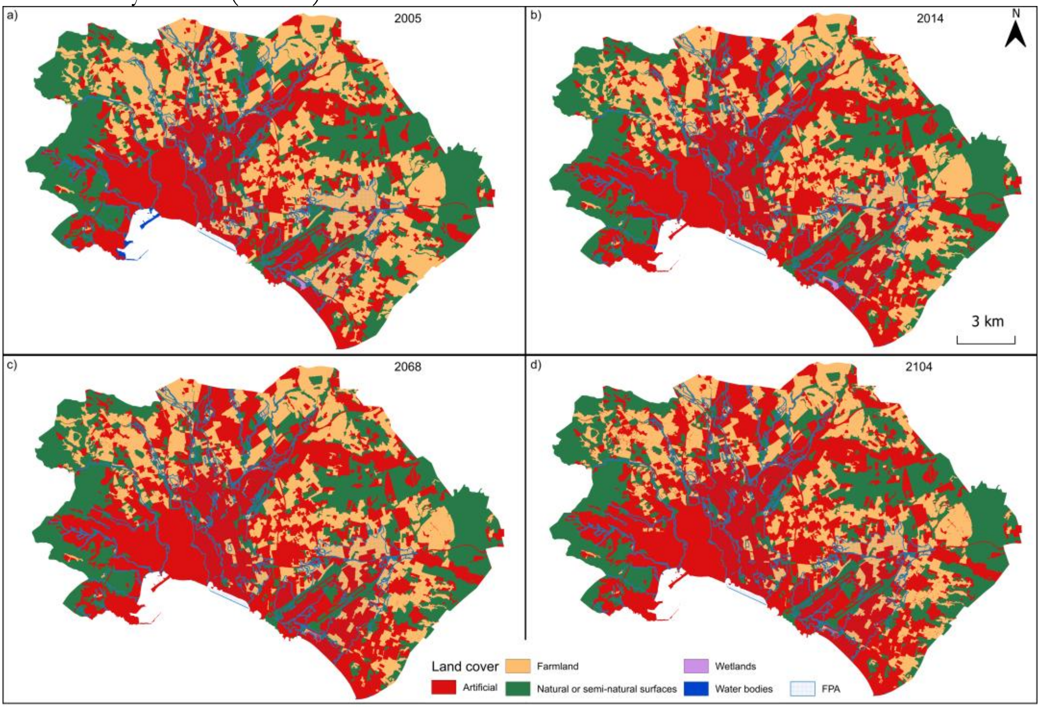


***Figure 2:*** *a) Observed land cover for 2005. b) Observed land cover for 2014. c) Projected land cover for 2068. d) Projected land cover for 2104.*

Land cover projections predicted an increase in artificial surfaces from 0.95% (238 ha) for the period 2014-2032, to 0.74% (183 ha) for the period 2086-2104. Overall, this supposes an increase of 3.8% between 2014-2104, which means 957 ha in 90 years and an average of 10.6 ha/year. These results follow the trend of an urban growth of 3.85% between 1956 and 2000 for the Balearic Islands (Pons, 2003), but reducing the exacerbated growth of two folding the artificial surfaces in Spain between 1990 and 2018 (Copernicus Programme, 2018). Despite that, the presented projections may be skewed by the uncertainty of future socio-political trends which may facilitate or restrict new urbanisations, as well as economic dynamics which could favour new infrastructure investments.

Regarding future population projections, an annual growth rate of 0.81% was obtained between 2005 and 2014, following a similar growing trend to the projections of 1.2% made by the regional authorities for the period 2020-2035 (CESIB, 2021). This rate of growth captures the algid phase of the Spanish property bubble, up to 2008 when it blew off and caused a deep crisis until 2014. The favourable socioeconomic context led to a population development, stabilised during the recession phase. After the recession the city followed a "recovering" process (CAGR for 2015-2019 of 1%), similarly to other big and medium cities in Spain (Gil-Alonso et al., 2021), and continuing with the 1900-2011 trend between 1%-2% (Zuniga et al., 2012). Contrary, during the COVID-19 pandemic, this trend was reversed, and urban areas slowed down their demographic growth (Reus-Pons et al., 2024). Applying this rate, considering an exponential annual growth, future population is shown in Table 1. The effect of cumulative growth is appreciated, since by 2104 population would double current population, achieving over 900,000 inhabitants.

**Table 1:** Future population projections. TGR = total growth rate. AG = Annual growth. FPA = Within the flood prone area. For the TFGF 2014 = 100%

| Year | Population | TGR | AGR | Population FPA | TGR FPA | AGR FPA |
|---|---|---|---|---|---|---|
| 2032 | 503,251 | 115.8% | 0.88% | 138,691 | 114,73% | 0,82% |
| 2050 | 582,728 | 134.1% | 0.95% | 159,947 | 132,32% | 0,90% |
| 2068 | 674,757 | 155.3% | 1.02% | 184,424 | 152,57% | 0,97% |
| 2086 | 781,319 | 179.8% | 1.11% | 212,622 | 175,89% | 1,05% |
| 2104 | 904,710 | 208.2% | 1.20% | 245,112 | 202,77% | 1,14% |

Spatially, in 2005 the rate of inhabitants per artificial pixel was $175*10^{-4}$, whereas by 2014 it descended to $156*10^{-4}$, due to the growth in artificial surfaces (7.6%) and the relatively shorter growth in population (7.04%). For future scenarios these rates go from $202*10^{-4}$ in 2032, to $299*10^{-4}$ by 2104, triggered by the steep demographic growth projected. Regarding the artificialisation process and population growth, in Figure 3 results are shown. On the one hand, the artificialisation process is previewed to be higher around the city (8.6% y 2104), while within the FPA artificial surfaces are expected to increase by 3.5% by 2068, and up to 5.8% by 2104, taking 2014 as a benchmark. This reduced development inside the FPA is explained by the existing previous urban development of these areas (Ruiz-Pérez et al., 2023), which was over 63%, and achieved 67% by 2104, whereas in the whole study area the artificial surfaces increased from 44.6% in 2014, to 48.4% by 2104.
On the other hand, population growth was the main factor triggering future vulnerability scenarios, due to its exponential increase. This growth follows similar patterns in the study area and within the FPA. In that case, population is expected to increase over 50% by 2068, and to twofold by 2104, meaning that approximately 245,000 people will be living in urban areas potentially affected by flash floods, the main natural risk posing a significant threat to the Balearic Islands.

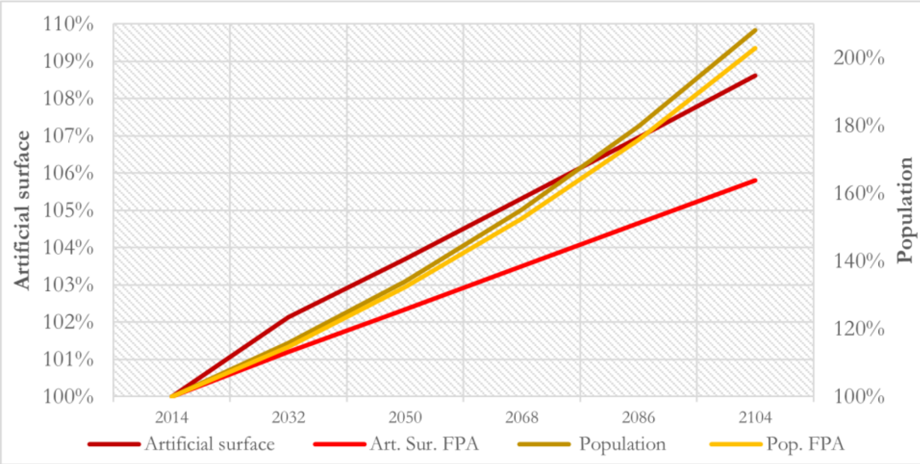


***Figure 3:*** *Projections of relative growth (2014=100%) for artificial surfaces and population for the whole study area, and for the FPA.*

## 6. Conclusions

Population trends show a huge development for the next decades, over two folding, based on witnessed growth. To allocate all these new population, both dwellings and services must be built, thus, non-artificial surfaces will be transformed into new urban spaces, increasing up to nearly 4% in 90 years. These two processes, population growth and artificialisation, were projected for 5 18-year scenarios from 2014 to 2104 (90 years), to generate novel projections of inhabitants and land covers at the most populated urban continuum of the Balearic Islands.

Flash floods are the main natural risk threatening the Balearics and affecting especially certain urban environments at Palma's Basin. The generated future scenarios were overlayed with FPA cartography to assess how many of this growth will be within flood risk environments. These results showed a similar increasing trend in population from 0.8% to 1.2% annually in the study area and within the FPA. Otherwise, the urbanisation process does not follow the same tendency within or without the FPA. While the potential urbanisation inter-scenario rate within the study area goes from 2.1% in 2032, to 1.5% by 2104, the artificial growth inter-scenario rate goes from 1.2% to 1.1% for the mentioned scenarios.

Therefore, the analysis was based on simple previous data used to estimate future behaviours: CAGR applied to an exponential decay function, and land cover projections reckoned on a 9-year period land cover changes, and without considering urban planning nor variations in population densities across the city. Even that, the obtained results allowed to quantify the magnitude of urban and demographic (over)development for the study area, and this data should be used to 1) develop more resilient urban planning avoiding the urbanisation of flood-prone areas, and adapted to the potential new risk scenarios threatening the society, and 2) aware the society of the risks which they are

exposed to. Follow these two guidelines would contribute to build a safer urban space and a more resilient society, conscious of their exposure to flood hazard.
Future works should develop more complex demographic projections and urban planning-related land cover changes to calculate more fine-grained risk scenarios for urban environments, based on the witnessed demographic growth and the increase in recurrence and intensity of extreme rainfall events causing flash floods.

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