Assessing Flood Vulnerability in the Ikopa Basin Through Integrated Hydrospatial Modelling: Hypsometry, Hydrography, Rainfall Patterns, Discharge Dynamics and Spatial Risk Correlations in the Antananarivo Plain

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Abstract: This study assesses flood vulnerability in the Ikopa Basin through an integrated hydrospatial modelling approach applied to the Antananarivo Plain. The analysis combines hypsometry, hydrography, rainfall patterns, observed discharge dynamics and spatial risk correlations to identify the physical and hydrological controls of flood-sensitive areas. The watershed covers 14,125.7 km², with a perimeter of 452.1 km and a hydrographic network of 3,047.4 km. Altitude ranges from 1,245 m to 1,900 m, producing a relief of 655 m, while the Ikopa River extends over 138.3 km with a low longitudinal slope of 0.47%. Rainfall distribution shows strong seasonality, with monthly peaks reaching 307–323 mm at Mahitsy Kely and Anosizato, and 315–321 mm at Ambohimanambola. Observed discharges indicate major wet-season peaks, reaching approximately 330 m³/s at Mahitsy Kely and 270–280 m³/s at Anosizato. The spatial correlation matrix confirms that flood risk is strongly associated with altitude score and distance score, both at 0.76, and with overall pressure at 0.77. These results show that flood vulnerability results from the combined effects of low altitude, hydrographic convergence, seasonal discharge peaks and spatial pressure.

Keywords: *Ikopa Basin; Flood Vulnerability; Hydrospatial Modelling; Rainfall–Discharge Dynamics; Spatial Risk Correlation.*

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I. INTRODUCTION

Urban flood vulnerability has become a major concern in many low-lying and rapidly urbanizing watersheds, where hydrological hazards are intensified by land-use pressure, insufficient drainage capacity and increasing exposure of populations and infrastructures. Climate change is expected to modify the frequency and intensity of extreme rainfall events, while urban expansion often reduces natural infiltration and storage areas, thereby increasing runoff and flood susceptibility [1]. Integrated urban flood risk management therefore requires a spatial understanding of both physical processes and territorial vulnerability, especially in cities located in floodplains [2]. In this context, hydrospatial modelling provides a relevant framework for analysing the interaction between topography, hydrography, rainfall distribution, discharge dynamics and spatial risk indicators. Rainfall–runoff relationships are particularly important because they explain how precipitation is transformed into river discharge according to catchment characteristics, antecedent wetness, drainage structure and response time [3]. Such an approach is also consistent with socio-hydrological thinking, which considers water systems and human systems as interdependent components of the same territorial process [4]. The Ikopa Basin and the Antananarivo Plain represent a significant case for this type of analysis. The plain is located in a low-altitude urban environment where river convergence, weak slopes and

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hydraulic structures shape the spatial distribution of flood vulnerability. Previous research on Antananarivo has shown that urbanization has increased exposure to flooding; in 2018, about 32% of the population of the agglomeration lived in flood-prone areas [5]. Recent work on flood mapping in data-poor urban environments also confirms the need for comparative and spatially explicit approaches adapted to contexts where hydrological and topographic information may be incomplete or unevenly distributed [6]. This study assesses flood vulnerability in the Ikopa Basin through integrated hydrospatial modelling, with a specific focus on the Antananarivo Plain. It combines hypsometric analysis, hydrographic structure, rainfall patterns, observed discharge dynamics and spatial correlation analysis of risk and pressure indicators. Interpolated surfaces are used to spatialize key variables and to support the interpretation of flood-sensitive areas from point-based and vector-based information [7]. The computational workflow relies on reproducible geospatial processing, allowing cartographic outputs, statistical indicators and scientific visualizations to be generated consistently [8]. The objective is to identify how low altitude, river proximity, rainfall seasonality, discharge peaks and spatial pressure combine to explain flood vulnerability in the Antananarivo Plain. By integrating morphometric, hydrological and spatial correlation indicators, the study aims to provide a synthetic interpretation of the hydrospatial functioning of the Ikopa system and to support flood-risk analysis at the watershed scale.

II. MATERIALS AND METHODS

The materials used in this study consisted mainly of geospatial vector data and hydroclimatic tabular data related to the Ikopa Basin and the Antananarivo Plain. The cartographic layers were obtained from the Foiben-Taosarintanin'i Madagasikara (FTM), the national mapping agency of Madagascar. These shapefiles provided the spatial basis for representing the river network, roads, administrative or basin limits, and topographic features required for the hydrospatial analysis [9]. Hydrological and rainfall data were obtained from the Autorité pour la Protection contre les Inondations de la Plaine d'Antananarivo (APIPA). These data were structured in CSV format and corresponded to five pluviometric and hydrometric stations used to analyse rainfall patterns, discharge dynamics and flood-related spatial behaviour within the Antananarivo Plain [10]. The processing environment was developed in Python because it allows reproducible geospatial analysis, numerical computation and scientific visualization within the same workflow. The script used several standard Python modules, including pathlib, shutil, tempfile, math, re and warnings, for file management, temporary directory handling, mathematical operations, text processing and warning control. The main scientific libraries were NumPy, pandas, GeoPandas and Matplotlib, which were used respectively for numerical calculations, tabular data processing, geospatial vector analysis and cartographic or graphical visualization [11], [12], [13], [14]. Geometric operations were performed with Shapely, particularly through box, Point, LineString, MultiLineString, GeometryCollection and unary_union, while coordinate transformations were managed using pyproj. Transformer [15], [16]. The first methodological step consisted of preparing and harmonizing the spatial data. The shapefiles were read with GeoPandas, checked for missing or invalid coordinate reference systems, and reprojected into WGS 84 / UTM Zone 38S in order to work in metric coordinates. This projection was selected because it allows coherent measurements of distance, area, perimeter and proximity within the study area. Invalid or empty geometries were removed, and the relevant spatial layers were clipped to the extent of the Ikopa Basin and the Antananarivo Plain. This preparation made it possible to standardize all vector data before producing the maps. The hydrographic network was then analysed by isolating the main rivers, especially the Ikopa and Sisaony, from the other drainage lines. The shapefile attributes and spatial relationships were used to distinguish the principal rivers from secondary streams. The river network was represented together with roads, basin boundaries, altitude zones and flood-sensitive sectors in order to build an integrated hydrospatial interpretation of the study area. The use of LineString, MultiLineString and unary_union made it possible to merge, simplify and analyse linear hydrographic features for mapping and distance-based interpretation. The CSV files from the five APIPA stations were processed with pandas. The rainfall and discharge data were organized by date and station, then converted into hydrological time series. Monthly rainfall totals, observed discharge variations and station-based comparisons were computed in order to produce rainfall histograms and discharge curves. The temporal analysis followed the hydrological year logic, with particular attention to the wet season, recession period and dry season. This made it possible to compare rainfall concentration and discharge response across the selected stations. The cartographic outputs were produced by combining vector layers, interpolated surfaces and thematic symbols. Altitudinal zoning was obtained by classifying elevation values into interpretable classes, while flood-sensitive areas were represented through spatial overlays involving low-altitude sectors, proximity to rivers and hydrographic convergence zones. The maps were completed with legends, scale bars, north arrows, coordinate grids and explanatory notes using Matplotlib graphical elements, including Rectangle patches for legend construction. This ensured that the figures were not only analytical outputs, but also publication-ready cartographic products. The graphical outputs were generated using Matplotlib from the processed CSV data and spatial indicators. The monthly rainfall histograms were used to compare seasonal rainfall distribution between the stations, while the discharge time-series curves were used to analyse observed hydrological dynamics from 2021 to 2024. In addition, spatial correlation matrices were produced from the modelled variables, including altitude, slope, distance to the hydrographic network, flood-risk score, urbanization pressure, environmental pressure and overall pressure. These matrices allowed the study to identify the statistical relationships between physical exposure and spatial vulnerability. The overall methodological approach therefore combined institutional geospatial data, APIPA station records, Python-based spatial processing, hydrological time-series analysis and scientific visualization. This workflow made it possible to produce the main cartographic and graphical results of the

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study, including hypsometric maps, hydrographic maps, rainfall distribution figures, discharge dynamics, interpolated altimetric surfaces, flood-sensitive areas and hydrospatial risk correlation matrices. The method is reproducible because each operation, from data reading to figure export, was implemented through a scripted Python workflow.

III. RESULTS

➤ *Hydrospatial Structure and Floodplain Zoning of the Ikopa Watershed at Farahantsana, Antananarivo Plain*

The figure below presents the hydrospatial organization of the Ikopa watershed at Farahantsana, with particular attention to the Antananarivo Plain, the main drainage axes, the floodplain, dikes, altitude zones and key interpretative points. The map is produced in UTM 38S coordinates and covers an approximate spatial extent from 720,000 m to 840,000 m East and from 7,820,000 m to 7,940,000 m North. It combines the Ikopa River, the Sisaony River, secondary drainage lines, roads, watershed limits and altitude classes ranging from below 1250 m to above 1600 m. The 20 km scale bar indicates that the flood-prone system is not a localized feature, but a continuous hydrographic and geomorphological unit extending over several tens of kilometres.

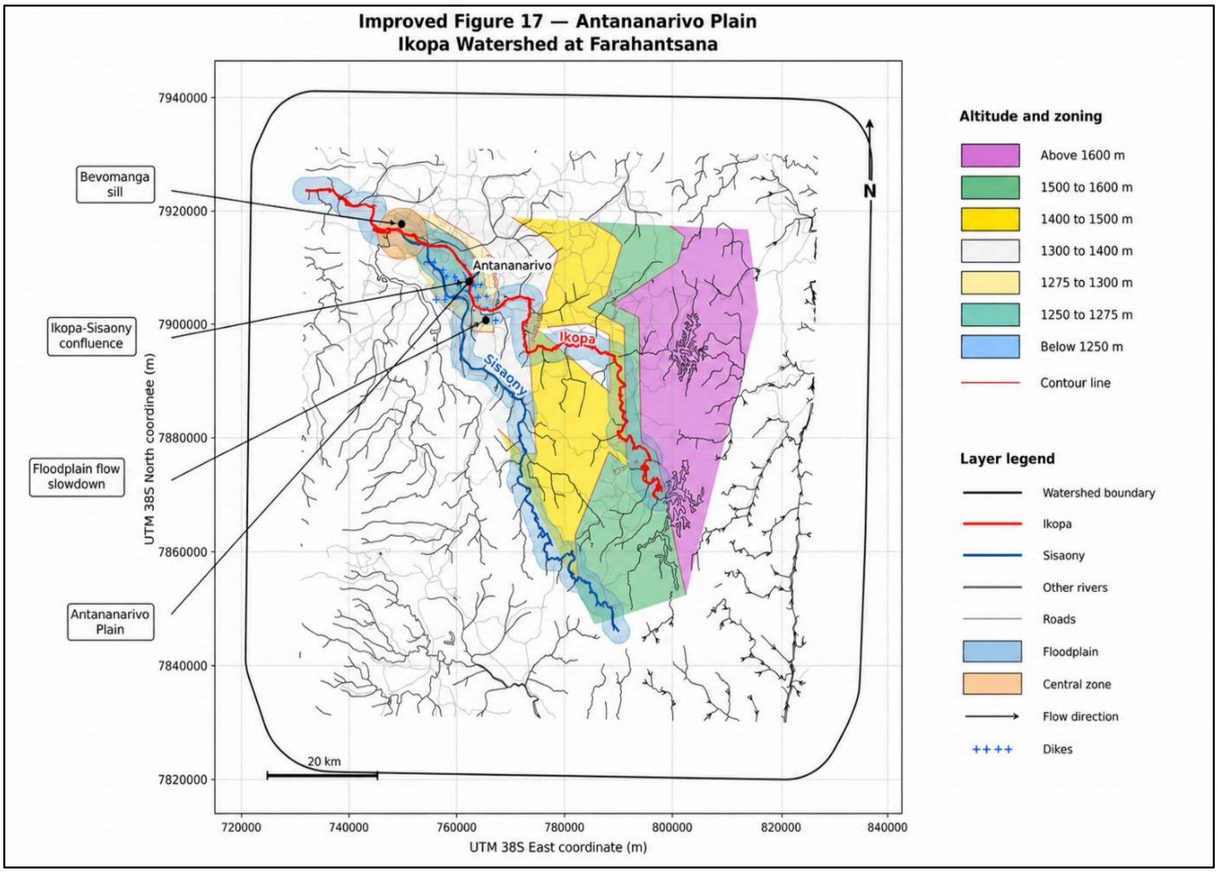

Fig 1 Hydrospatial Structure and Floodplain Zoning of the Ikopa Watershed at Farahantsana, Antananarivo Plain.

This figure shows a marked contrast between the low-lying Antananarivo Plain and the higher eastern and south-eastern sectors of the basin. The lowest altitude classes, below 1250 m and between 1250 and 1275 m, are mainly associated with the floodplain corridor along the Ikopa and Sisaony rivers. These areas correspond to zones where water accumulation and slow drainage are more likely to occur. In contrast, the 1500 to 1600 m class and the areas above 1600 m are located farther east, indicating higher relief sectors that contribute to upstream runoff generation. This altitudinal gradient explains the general direction of water movement from the elevated upstream zones toward the lower central and western parts of the basin. The Ikopa River, represented as the main red drainage axis, structures the hydrological functioning of the mapped area. It receives contributions from secondary streams and interacts with the Sisaony River in the confluence zone. The Ikopa-Sisaony confluence is a key hydrological sector because it concentrates flows from two major drainage systems. This spatial convergence increases the hydraulic sensitivity of the plain, especially when rainfall-generated runoff from upstream areas reaches the low-gradient floodplain. The blue floodplain area indicates the zones where overflow, storage and lateral spreading of water may occur during high-flow periods. The Bevomanga sill appears as an important geomorphological control point. Its position downstream of the central plain suggests a possible constraint on the evacuation of floodwaters. When flows increase, this sill may contribute to a slowdown of drainage, reinforcing water retention within the Antananarivo Plain. The labelled area of floodplain flow slowdown confirms that the vulnerability of the plain is not only related to river proximity, but also to the reduced slope and to the hydraulic control exerted by downstream morphological thresholds. The central zone, shown in orange, occupies a strategic

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position near the confluence and within the low-altitude floodplain system. This area is particularly important because it lies at the intersection of urban exposure, hydraulic convergence and low topographic relief. The presence of dikes, represented by blue cross symbols, indicates that flood protection structures have been established to control or limit overflow. However, the need for such structures also confirms the intrinsic sensitivity of this part of the basin. Dikes may reduce direct flooding under ordinary conditions, but their effectiveness depends on maintenance, flow magnitude, channel capacity and the ability of the drainage system to evacuate water toward the downstream outlet.

➢ *Hypsometry, Hydrography and Rainfall Distribution in the Ikopa Basin*

The following figure provides an integrated representation of the Ikopa Basin by combining hypsometric classes, the hydrographic network, annual isohyets and monthly rainfall regimes at selected stations. It is designed to show how topography, river organization and rainfall variability interact within the basin, from the higher eastern and southeastern sectors to the lower western plain. The map therefore offers a synthetic view of the physical controls that structure water circulation and hydrological response in the Ikopa system.

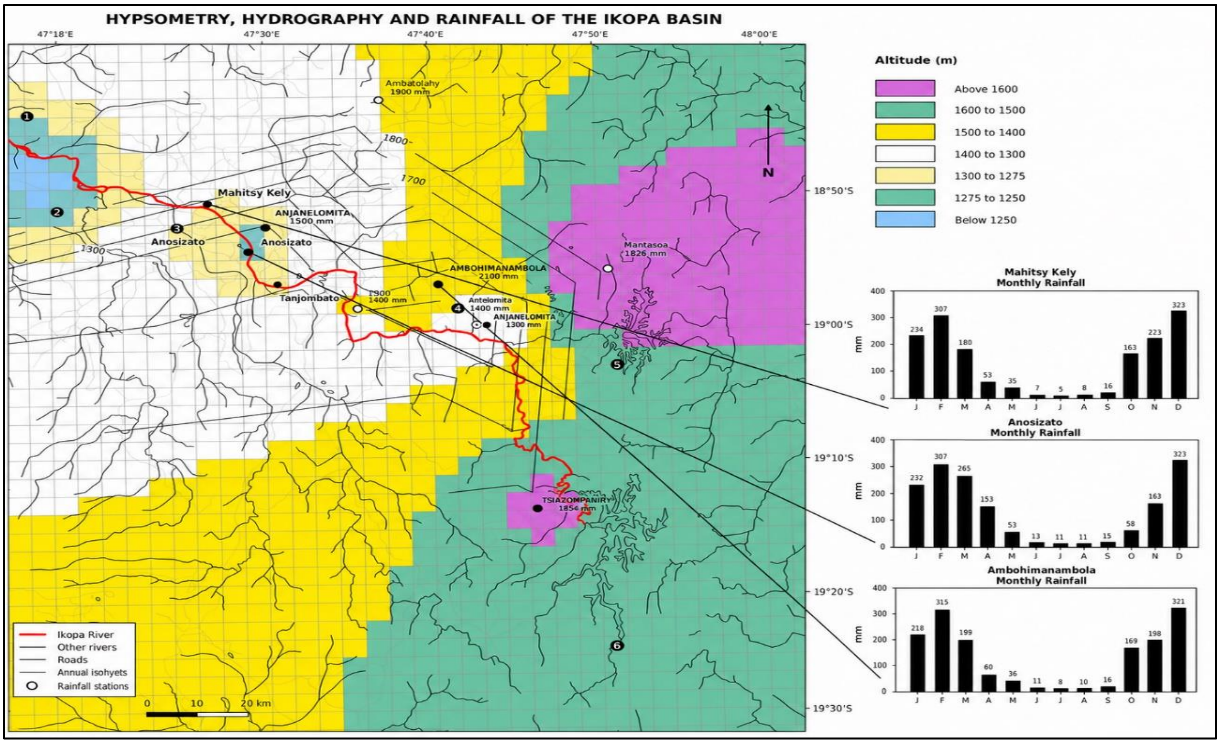

Fig 2 Hypsometry, Hydrography and Rainfall Distribution in the Ikopa Basin.

The spatial pattern of altitude reveals a clear contrast between the elevated upstream zones and the lower downstream plain. The eastern and southeastern parts of the basin are dominated by altitude classes between 1500 and 1600 m and by sectors above 1600 m, whereas the western and northwestern parts are characterized mainly by lower classes ranging from 1250 to 1300 m, 1275 to 1250 m and locally below 1250 m. This altitudinal gradient confirms that the basin is organized around a general upstream–downstream transition, in which runoff generated in the higher reliefs progressively converges toward the low-lying plain. Such a configuration is essential for understanding the concentration of flows and the increasing sensitivity of the western plain to water accumulation. The hydrographic network reinforces this interpretation. The Ikopa River, highlighted in red, forms the main drainage axis of the basin and links the upstream sectors to the lowland plain. Secondary rivers, shown in black, complete a relatively dense network that channels runoff toward the principal stream. The location of rainfall stations and the annual isohyets indicate that the basin does not receive rainfall uniformly. Isohyet values visible on the map, notably around 1300 mm, 1400 mm, 1700 mm and 1800 mm, show a marked pluviometric gradient, with higher rainfall generally associated with the higher reliefs and lower rainfall observed toward the western lowlands. The monthly rainfall diagrams further illustrate the seasonal nature of precipitation. At Mahitsy Kely, rainfall reaches 234 mm in January, 307 mm in February and 323 mm in December, while it drops to only 7 mm in June, 5 mm in July and 8 mm in August. At Anosizato, the wet season is similarly pronounced, with 232 mm in January, 307 mm in February, 265 mm in March and 323 mm in December, whereas the dry season records only 13 mm in June, 11 mm in July, 11 mm in August and 15 mm in September. At Ambohimanambola, the same seasonal regime appears, with 218 mm in January, 315 mm in February, 199 mm in March and 321 mm in December, compared with only 11 mm in June, 8 mm in July and 10 mm in August. These values clearly indicate that rainfall is strongly concentrated during the austral summer, while the austral winter is marked by a pronounced hydrological deficit. This seasonal rainfall regime has important hydrological implications. During the rainy season, the combination of high monthly precipitation and elevated upstream terrain increases the production of

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runoff, which is then transferred through the hydrographic network toward the lower parts of the basin. The concentration of high rainfall values in stations such as Ambatolahy, where annual rainfall is indicated at 1900 mm, and Mantasoa, where it reaches 1826 mm, suggests that the eastern highlands act as major water-producing zones. In contrast, the lower western plain, including the Mahitsy Kely and Anosizato sectors, functions more as a receiving and transit area than as a rainfall-generating zone. This explains why flood risk in the plain cannot be interpreted only from local rainfall totals, but must also account for the upstream contribution of the higher and wetter sectors. The figure also reveals the close relationship between rainfall distribution and topographic control. The wetter areas are generally associated with higher altitude classes, while the lower western plain corresponds to lower annual rainfall values but higher hydraulic sensitivity. In other words, the most exposed zones are not necessarily those receiving the greatest local rainfall, but rather those situated at lower altitude, along the main drainage corridor, where runoff from the upstream highlands converges. This relationship is central to the hydrological functioning of the Ikopa Basin because it shows that topographic position and network connectivity strongly influence the spatial distribution of hydrological pressure.

- *Observed Discharge Dynamics at Ikopa Hydrometric Stations During the 2021–2024 Hydrological Years*

This figure presents the temporal evolution of observed discharges at five hydrometric stations of the Ikopa system over the 2021–2024 hydrological period. The stations represented are Mahitsy Kely, Anosizato, Ambohimanambola, Antelomita and Tanjombato. Discharge is expressed in cubic metres per second, while time is organized according to hydrological years, from November 2021 to late 2024. The seasonal background shading helps distinguish the main hydrological phases, namely the rising discharge period from November to February, the recession period from March to April, and the low-flow period from May to October.

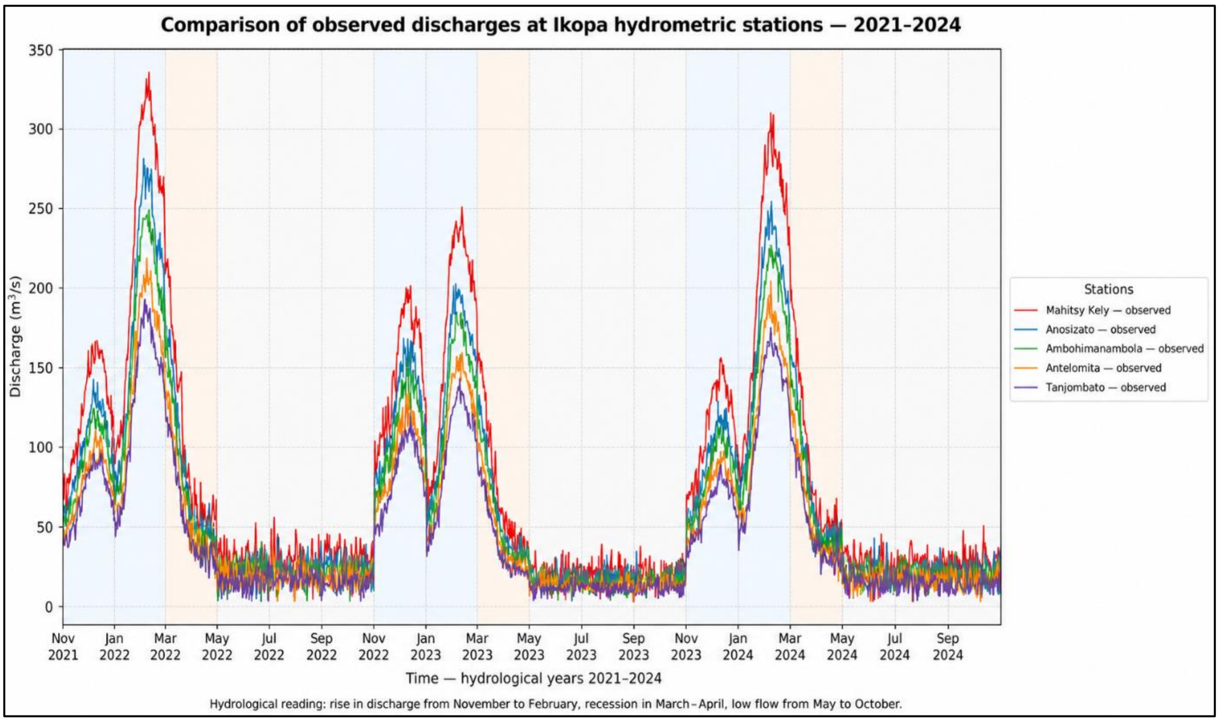

Fig 3 Observed Discharge Dynamics at Ikopa Hydrometric Stations During the 2021–2024 Hydrological Years

The figure shows a clear seasonal discharge regime, with repeated increases during the rainy season and marked reductions during the dry season. The first major hydrological peak occurs in early 2022, when discharge rises sharply at all stations. Mahitsy Kely records the highest response, with a peak reaching approximately 330 m^3/s, while Anosizato reaches around 270 to 280 m^3/s. Ambohimanambola also shows a strong rise, close to 240 to 250 m^3/s, whereas Antelomita and Tanjombato remain comparatively lower, with maximum values of about 210 m^3/s and 185 to 190 m^3/s respectively. This first peak indicates a highly active wet season and confirms the rapid response of the Ikopa hydrological system to rainfall inputs. After the early 2022 peak, discharge decreases progressively during March and April, before reaching low-flow conditions from May to October. During this dry-season period, most stations remain below approximately 40 m^3/s, with frequent values between 10 and 30 m^3/s. This sharp contrast between wet-season peaks and dry-season baseflows highlights the strong seasonal variability of the basin. It also shows that the Ikopa system alternates between short periods of high hydraulic pressure and longer periods of reduced flow. The 2022–2023 hydrological year presents a less intense but still visible discharge response. Two main increases are observed between November 2022 and March 2023. The first rise reaches approximately 200 m^3/s at Mahitsy Kely, while the second peak approaches 240 to 250 m^3/s. At Anosizato, the corresponding peaks are around 160 to 200 m^3/s.

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Ambohimanambola remains slightly lower, while Antelomita and Tanjombato display more moderate responses. This pattern suggests that the hydrological year 2022–2023 was active but less extreme than the 2021–2022 wet season. The 2023–2024 hydrological year shows another strong discharge episode, especially between January and March 2024. Mahitsy Kely again records the highest values, with a maximum of about 310 m³/s. Anosizato reaches nearly 250 m³/s, while Ambohimanambola rises to approximately 220 m³/s. Antelomita and Tanjombato remain lower, with peaks around 180 m³/s and 165 m³/s. The repeated dominance of Mahitsy Kely suggests that this station occupies a downstream position where flows from several upstream and intermediate sectors are accumulated. The comparison between stations reveals a consistent hierarchy of discharge magnitude. Mahitsy Kely is generally the most reactive and records the highest peaks throughout the series. Anosizato and Ambohimanambola show intermediate to high values, reflecting their important role in the central and upstream parts of the system. Antelomita and Tanjombato display lower discharge values, but their seasonal variations remain synchronized with the other stations. This synchronization indicates that all stations respond to the same hydrological forcing, mainly the seasonal rainfall regime, although their magnitudes differ according to position, drainage contribution and local hydraulic conditions. Scientifically, the figure confirms that the Ikopa Basin has a strongly seasonal hydrological behaviour. The wet season produces rapid and intense increases in discharge, especially from November to February, while March and April correspond to a recession phase during which flows decline progressively. From May to October, the basin enters a low-flow regime characterized by weak and relatively stable discharges. The observed peaks above 300 m³/s at Mahitsy Kely and above 250 m³/s at Anosizato indicate periods of high hydraulic load, which may increase flood susceptibility in downstream and low-lying sectors of the Antananarivo Plain.

- *Interpolated Altimetric Surfaces, Hydrography and Flood-Sensitive Areas in the Antananarivo Plain Watershed*

This figure presents the spatial organization of the Antananarivo Plain Watershed through an integrated cartographic representation of interpolated altimetric surfaces, altitude lines, hydrography and flood-sensitive areas. The map is projected in UTM 38S coordinates and combines the watershed boundary, the Ikopa River, the Sisaony River, secondary drainage lines, roads, altitudinal zoning and morphometric indicators. It provides a synthetic spatial basis for understanding how relief, drainage structure and low-lying zones interact in the formation of flood vulnerability within the plain.

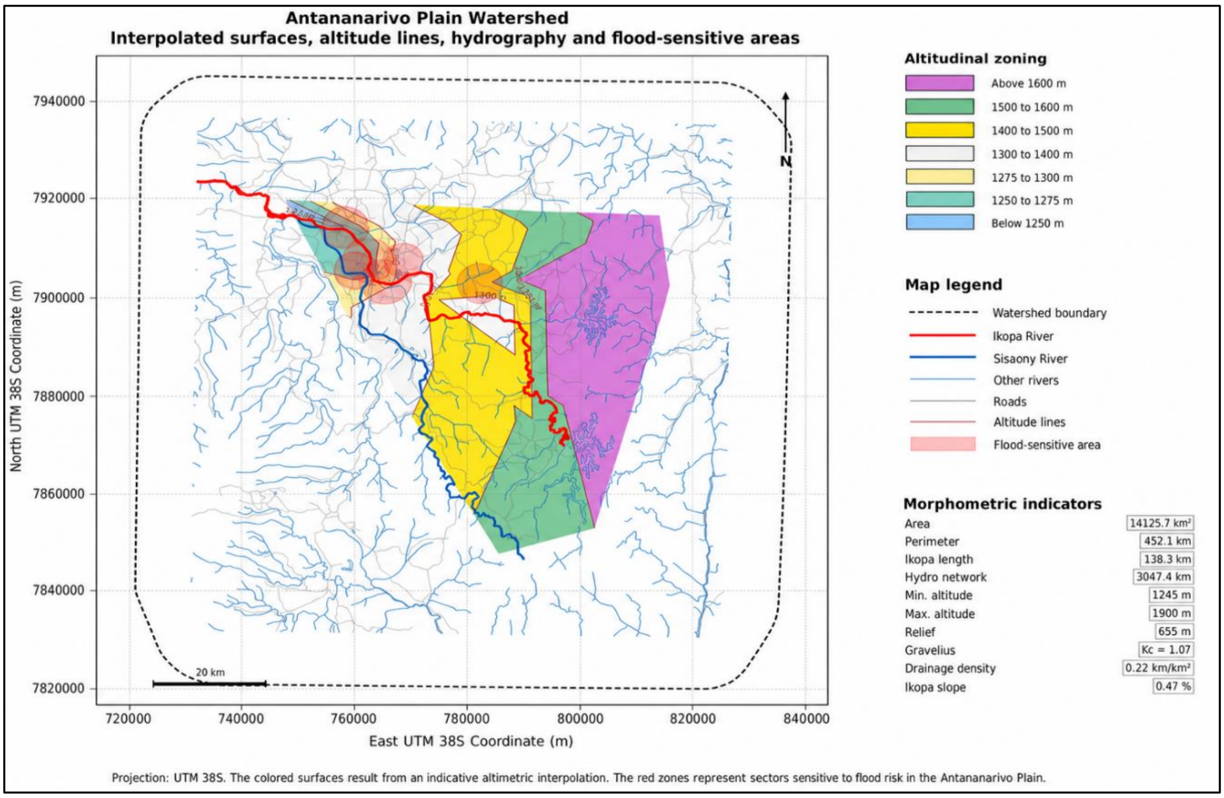

Fig 4 Interpolated Altimetric Surfaces, Hydrography and Flood-Sensitive Areas in the Antananarivo Plain Watershed

The morphometric indicators show that the studied watershed covers an area of 14,125.7 km², with a perimeter of 452.1 km. The Ikopa River extends over 138.3 km within the mapped system, while the total hydrographic network reaches 3,047.4 km. These values indicate a large drainage basin with a developed river network, capable of collecting and transferring runoff from several upstream and lateral sectors toward the Antananarivo Plain. The drainage density, estimated at 0.22 km/km², suggests a moderately distributed hydrographic network, but its spatial concentration around the main valleys remains important for interpreting flood-prone sectors. The altimetric structure reveals a clear contrast

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between the low-lying western and central parts of the watershed and the higher eastern sectors. The minimum altitude is 1,245 m, while the maximum altitude reaches 1,900 m, giving a total relief of 655 m. This difference in elevation confirms the existence of a marked topographic gradient between the upstream reliefs and the lower plain. The areas below 1,250 m and between 1,250 and 1,275 m are mainly associated with the lower drainage corridors, whereas the classes above 1,500 m and above 1,600 m appear more clearly toward the eastern and southeastern parts of the watershed. This configuration favours the transfer of runoff from elevated sectors toward the lower central plain. The Ikopa River, represented as the main red hydrographic axis, structures the spatial functioning of the watershed. Its course crosses the basin and connects the upstream sectors to the low-lying areas of the Antananarivo Plain. The Sisaony River, shown in blue, contributes to the drainage system and reinforces the convergence of flows toward the central and western parts of the plain. The dense network of other rivers, represented in light blue, shows that the flood dynamics cannot be understood only from the main river channel, because secondary streams also contribute to runoff concentration during rainy periods. The red flood-sensitive areas are located mainly near the low-altitude sectors and close to the main hydrographic axes. Their position shows that flood sensitivity is linked to the combined effect of low elevation, river proximity and convergence of flows. These areas correspond to zones where water may accumulate or where drainage may become slower during high-flow conditions. The presence of altitude lines around these sensitive zones also suggests that slight topographic variations can influence water circulation, especially in a plain where the general slope is weak. The Gravelius coefficient, indicated as Kc = 1.07, suggests that the basin shape is relatively compact. A compact watershed can favour a more rapid hydrological response, because runoff generated in different parts of the basin may reach the main drainage system within a shorter time interval. Combined with the large watershed area and the extensive hydrographic network, this compactness may contribute to the concentration of flows in the downstream plain during intense rainfall events. The slope of the Ikopa, estimated at 0.47%, confirms the low-gradient character of the main drainage axis in the studied sector. Such a weak slope can reduce the speed of water evacuation, particularly in the lower plain. This is important for flood interpretation, because even when discharge is not exceptionally high, slow drainage conditions may increase water retention, overflow and local flooding. The flood-sensitive areas therefore reflect not only the presence of watercourses, but also the hydraulic limitations imposed by low relief and reduced longitudinal slope.

➢ *Spatial Correlation Matrix of Hydrospatial Risk and Pressure Indicators in the Ikopa Basin*

This figure presents a spatial correlation matrix between the main variables used to assess hydrospatial vulnerability in the Ikopa Basin and the Antananarivo Plain. The matrix compares physical parameters, such as altitude, slope and distance to the hydrographic network, with synthetic indicators related to altitude score, distance score, slope score, flood risk, urbanization pressure, environmental pressure and overall pressure. The correlation coefficients range from -1.00 to 1.00, where positive values indicate variables evolving in the same direction, while negative values indicate opposite spatial relationships.

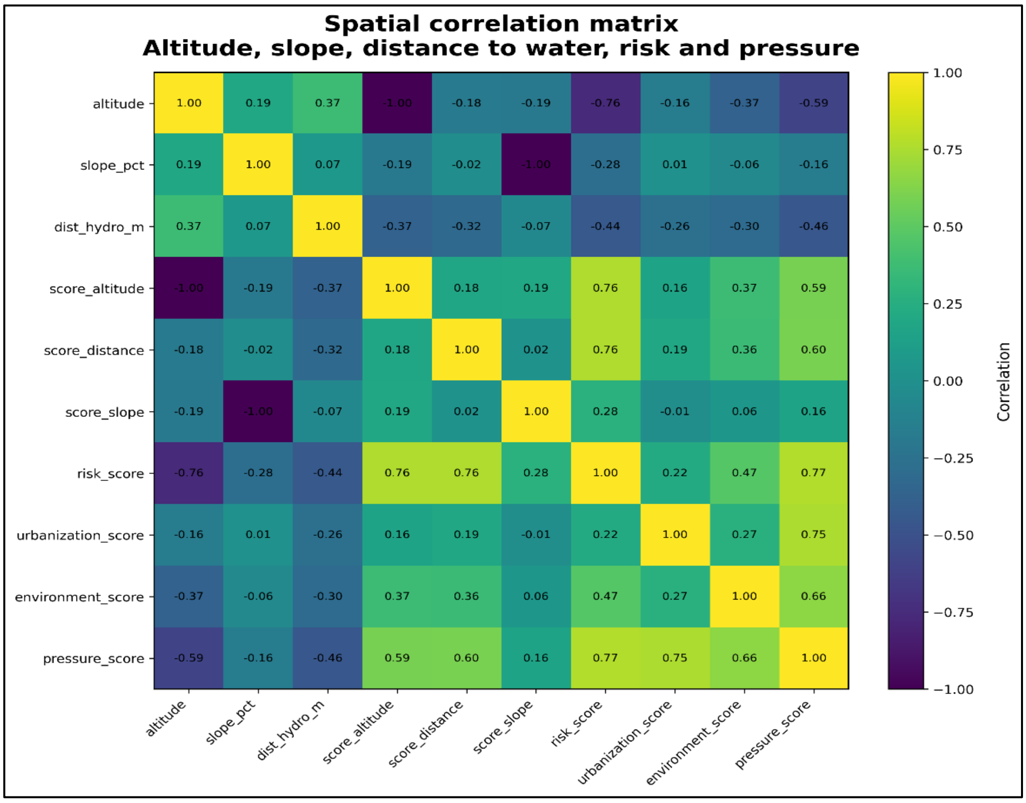

Fig 5 Spatial Correlation Matrix of Hydrospatial Risk and Pressure Indicators in the Ikopa Basin

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The matrix first shows a very strong negative correlation between altitude and altitude score, with a coefficient of -1.00. This result is expected because the altitude score was designed to give higher vulnerability values to low-altitude areas. In other words, when altitude increases, the altitude-related vulnerability decreases. This confirms that the low-lying sectors of the Antananarivo Plain are more sensitive in the hydrospatial model, whereas the higher reliefs are less directly associated with flood-prone conditions. Altitude is also negatively correlated with flood risk, with a coefficient of -0.76, and with overall pressure, with a coefficient of -0.59. These values indicate that lower areas are more strongly associated with high-risk and high-pressure conditions. The relationship is scientifically coherent because flood vulnerability in the plain is controlled partly by low elevation, weak drainage capacity and the tendency of water to accumulate in topographic depressions. The negative correlation between altitude and environmental score, estimated at -0.37, also suggests that environmentally sensitive zones are more frequent in lower sectors of the basin. The distance to the hydrographic network is negatively correlated with flood risk, with a coefficient of -0.44, and with overall pressure, with a coefficient of -0.46. This means that the closer an area is to rivers or drainage channels, the higher its level of modelled vulnerability. The correlation between distance to water and distance score is also negative, with a value of -0.32, which is consistent with the modelling logic: areas located near the hydrographic network receive a higher distance-related vulnerability score. Flood risk appears as one of the most structurally important variables in the matrix. It is strongly correlated with altitude score and distance score, both reaching 0.76. This indicates that flood risk is mainly controlled by the combined effect of low altitude and proximity to watercourses. The correlation between flood risk and pressure score is also high, with a coefficient of 0.77, showing that the areas identified as flood-prone are also the areas where global hydrospatial pressure is strongest. This confirms the central role of flood risk in the construction of the overall vulnerability pattern. Urbanization score is strongly correlated with pressure score, with a coefficient of 0.75. This result suggests that urban pressure contributes significantly to the overall spatial pressure in the Antananarivo Plain. Although its correlation with flood risk is weaker, at 0.22, urbanization remains important because it can increase vulnerability through land occupation, soil sealing, reduction of natural drainage areas and exposure of infrastructures or settlements. This means that urban pressure does not create flood risk alone, but it amplifies the consequences of hydrological constraints. The environmental score also shows a positive relationship with pressure score, with a coefficient of 0.66. This indicates that environmentally sensitive areas contribute clearly to the global pressure index. Its correlation with flood risk, estimated at 0.47, shows that environmental vulnerability and hydraulic risk partly overlap. Such a relationship may reflect the role of lowlands, wetlands, drainage corridors or degraded areas in the spatial distribution of flood sensitivity. Slope presents a particular behaviour in the matrix. The correlation between slope percentage and slope score reaches -1.00, which reflects the inverse construction of the score: lower slopes receive higher vulnerability values. The correlation between slope score and flood risk remains moderate, with a value of 0.28, while its relationship with pressure score is weaker, at 0.16. This suggests that slope contributes to flood sensitivity, but less strongly than altitude and proximity to water. In the Antananarivo Plain, flood risk is therefore more directly controlled by low elevation and hydrographic proximity than by slope alone.

IV. DISCUSSIONS

The results show that flood vulnerability in the Ikopa Basin is controlled by the combined influence of relief, hydrography, rainfall seasonality and spatial pressure in the Antananarivo Plain. The hypsometric analysis highlights a clear contrast between the higher upstream sectors and the lower plain, where weak slopes and low altitudes favour water concentration and slow drainage. This spatial configuration explains why the plain is more exposed to flooding than the surrounding elevated areas. The rainfall and discharge analyses confirm the strongly seasonal behaviour of the basin. High rainfall during the wet season generates rapid increases in discharge, especially at downstream stations such as Mahitsy Kely and Anosizato. These stations record the highest flow responses because they receive accumulated runoff from upstream and lateral drainage systems. Conversely, the dry season is characterized by low discharge values, showing a strong contrast between wet-season flood potential and dry-season baseflow conditions.

The cartographic results also show that flood-sensitive areas are mainly located near the main river corridors and low-altitude zones. This confirms that flood risk is not only related to rainfall intensity, but also to river proximity, topographic position and drainage capacity. The spatial correlation matrix supports this interpretation by showing strong relationships between flood risk, altitude-related vulnerability, distance to the hydrographic network and overall pressure. Overall, the study demonstrates that flood vulnerability in the Antananarivo Plain results from an interaction between natural hydrogeomorphological constraints and human spatial pressure. Integrated hydrospatial modelling is therefore useful for identifying critical areas, understanding flood mechanisms and supporting better watershed-scale flood risk management.

V. CONCLUSIONS

This study demonstrated the relevance of integrated hydrospatial modelling for assessing flood vulnerability in the Ikopa Basin and the Antananarivo Plain. By combining hypsometry, hydrography, rainfall patterns, discharge dynamics and spatial risk correlations, the analysis provided a coherent understanding of the physical and hydrological factors that control flood-sensitive areas. The results show that the Antananarivo Plain is particularly vulnerable because of its low altitude, weak slope, river convergence and proximity to the main hydrographic network. The upstream sectors contribute to runoff generation, while the lower plain functions as a receiving and accumulation area. This spatial organization explains the recurrent hydraulic pressure observed during the wet season. The rainfall and discharge

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analyses confirmed the strong seasonal behaviour of the basin, with high-flow periods concentrated between November and February, followed by recession and low-flow phases. The spatial correlation matrix further showed that flood risk is closely linked to altitude-related vulnerability, distance to rivers and overall spatial pressure. Overall, flood vulnerability in the Antananarivo Plain cannot be explained by a single factor. It results from the interaction between topographic constraints, hydrological processes, drainage structure and human occupation. Therefore, flood risk management should be planned at the watershed scale, with priority given to hydrological monitoring, drainage maintenance, protection of floodplain functions and control of urban expansion in exposed low-lying areas.

REFERENCES

[1]. IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. doi:10.1017/9781009157896.

[2]. Jha, A.K., Bloch, R. and Lamond, J., 2012. Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century. Washington, DC: World Bank. doi:10.1596/978-0-8213-8866-2.

[3]. Beven, K.J., 2012. Rainfall–Runoff Modelling: The Primer. 2nd ed. Chichester: John Wiley & Sons. doi:10.1002/9781119951001.

[4]. Sivapalan, M., Savenije, H.H.G. and Blöschl, G., 2012. 'Socio-hydrology: A new science of people and water', Hydrological Processes, 26(8), pp. 1270–1276. doi:10.1002/hyp.8426.

[5]. Ramiaramanana, F.N. and Teller, J., 2021. 'Urbanization and floods in Sub-Saharan Africa: spatiotemporal study and analysis of vulnerability factors—case of Antananarivo agglomeration, Madagascar', Water, 13(2), 149. doi:10.3390/w13020149.

[6]. Lema, M.Q., 2023. Étude du bilan hydrique et sédimentaire de l'Ikopa au niveau de la plaine d'Antananarivo : effet saisonnier. Mémoire de Master, Institut National des Sciences et Techniques Nucléaires, Université d'Antananarivo. doi:10.13140/RG.2.2.33908.26249.

[7]. Ramiaramanana, F.N., Munyi, J.M.M., Archambeau, P. and Teller, J., 2025. 'A comparative assessment of flood mapping methods for urban risk management in data-poor environments', Natural Hazards. doi:10.1007/s11069-025-07590-9 .

[8]. Foiben-Taosarintanin'i Madagasikara (FTM), 2023. Madagascar Report. Southern Africa and Islands Hydrographic Commission Meeting. Madagascar.

[9]. Bureau National de Gestion des Risques et des Catastrophes (BNGRC), n.d. Bureau National de Gestion des Risques et des Catastrophes. Antananarivo: BNGRC.

[10]. PRODUIR Madagascar, 2021. APIPA : Autorité pour la Protection contre les Inondations de la Plaine d'Antananarivo. Antananarivo: Projet de Développement Urbain Intégré et de Résilience.

[11]. Shepard, D., 1968. 'A two-dimensional interpolation function for irregularly-spaced data', Proceedings of the 23rd ACM National Conference, pp. 517–524.

[12]. Jordahl, K., Van den Bossche, J., Fleischmann, M., Wasserman, J., McBride, J., Gerard, J. and Leblanc, F., 2020. GeoPandas: Python tools for geographic data. Zenodo. doi:10.5281/zenodo.3946761.

[13]. McKinney, W., 2010. 'Data structures for statistical computing in Python', Proceedings of the 9th Python in Science Conference, pp. 56–61. doi:10.25080/Majora-92bf1922-00a.

[14]. Harris, C.R., Millman, K.J., Van der Walt, S.J., Gommers, R., Virtanen, P., Cournapeau, D. et al., 2020. 'Array programming with NumPy', Nature, 585, pp. 357–362. doi:10.1038/s41586-020-2649-2.

[15]. Hunter, J.D., 2007. 'Matplotlib: A 2D graphics environment', Computing in Science & Engineering, 9(3), pp. 90–95. doi:10.1109/MCSE.2007.55.