Application of Artificial Intelligence in the Evaluation of Positional Accuracy and Statistical Validation of Digital Elevation Models for Hydrological Studies

Osmar Cuentas Toledo[1], José Orlando Quintana Quispe[2], Maryluz Cuentas Toledo[3], Alberto Bacilio Quispe Cohaila[4], Aloísio Machado da Silva Filho[5]

[1]*Universidad Nacional de Moquegua - Perú, ocuentast@unam.edu.pe*
[2]*Universidad Nacional de Moquegua - Perú, jquintanaq@unam.edu.pe*
[3]*Universidad Nacional Micaela Bastidas de Apurímac - Perú, mcuentas@unamba.edu.pe*
[4]*Universidad Nacional Jorge Basadre Grohmann - Perú, abqcsama@yahoo.es*
[5]*Universidade Estadual de Feira de Santana – Brazil, aloisioestatistico@uefs.br*

This study uses artificial intelligence to comprehensively evaluate digital elevation models (DEMs), specifically SRTM, AlosPalsar, and ASTER, in the Moquegua region of Peru. Three recognized standards were used to evaluate the positional accuracy of DEMs: EMAS, NMAS, and NSSDA. The DEMs were also assessed through correlation, the coefficient of determination (R2) and the Bland-Altman Graph, which allowed us to understand and visualize the relationship and agreement between the elevations extracted from the DEMs and the altimetric control network of the national chart of Peru at a scale of 1:25000. The correlation and R2 revealed a solid relationship and a high degree of explanation for the variability of the elevations observed by the MDEs. The Bland-Altman plots confirmed the agreement between the elevations predicted by the MDEs and those observed at the points of the altimetric control network. This study highlights the importance and value of combining artificial intelligence techniques with statistical validation methods and positional accuracy standards to ensure the accuracy and reliability of EDMs in hydrological applications, thus providing a robust and verifiable framework for future research in this domain.

Keywords: Artificial Intelligence, Delimitation of Hydrographic Basins, Digital Elevation Models, Hydrological Studies, Positional Accuracy.

INTRODUCTION

The accuracy in the representation of the terrain using Digital Elevation Models (DEM) is a known problem in civil engineering and topography [1][2][3], being primary and most relevant spatial data for a wide variety of applications in hydrology [4]. The use of MDEs emerges as a fundamental pillar in the context of hydrological studies and hydrological modelling to plan, develop and manage water resources, which is addressed mainly by the precise delimitation of basins, hydrographic areas [5] as well as in the definition of their channels [6], influencing the hydrological modeling of hydrographic basins [4].

Digital elevation models (DEMs) are crucial for hydrology and water resources management. They provide a three-dimensional representation of the Earth's surface, which is essential for understanding and managing the flow and distribution of water, presenting several critical applications of DEMs in hydrology such as in watershed delineation [7][8][9][8][10][11], hydrological modeling [12], flood risk analysis [13][14], soil erosion and sediment transport [15][16], river and stream network analysis [17][18], rainfall-runoff analysis [19][20], wetland mapping and analysis [21][22], groundwater flow and recharge analysis [23][24], irrigation planning and management [25], climate change impact assessment [10][26].

In summary, DEMs are invaluable in hydrology because they provide detailed and accurate topographic information, critical for water resource management, flood control, conservation planning, and understanding hydrological processes in a changing climate [27][3]. There are several ways to represent Digital Elevation Models (DEM), the most common being the regular mesh DEM and the irregular triangular network (TIN) DEM [28].

Consequently, knowing the accurate delimitation of a hydrographic basin contributes to efficiently managing water resources for its inhabitants; consequently, poor delimitation causes social, economic and environmental conflicts. Therefore, interest was born in investigating the official delimitation of the hydrographic basin of the Moquegua River, managing to locate some errors in its delimitation. This study proposes to conduct a detailed evaluation of the positional accuracy and quality of MDEs. Specifically, those from SRTM, AlosPalsar and ASTER implement Artificial Intelligence techniques and statistical validation methods to manage water resources and strategy planning properly for sustainable development, providing a framework that contributes to the cartographic update of the delimitation of basins in Peru.

The general objective of the study is to evaluate the positional accuracy and quality of the delimitation of the Ilo-Moquegua hydrographic basin more realistic to the terrain, carried out by the Digital Elevation Models (MDEs) derived from SRTM, AlosPalsar and ASTER, through the application of Artificial Intelligence techniques, positional accuracy evaluation standards (EMAS, NMAS and NSSDA) and statistical validation methods, to determine their reliability and applicability in hydrological studies, specifically in the delimitation of hydrographic basins in the Moquegua region, Peru.

MATERIALS AND METHODS

2.1. Study Area

The Ilo-Moquegua hydrographic basin is located in southern Peru, in the department of Moquegua, mainly occupying the province of Mariscal Nieto. Geographically, it is between 250,000 to 350,000 meters east and 8,040,000 to 8,135,000 meters north in the Universal

Transverse Mercator (UTM) projection of the WGS 84 world geodetic system, as seen in Fig. 1.

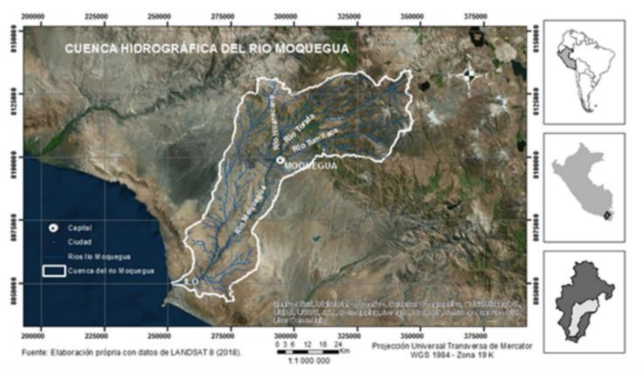

Fig. 1. Location of Moquegua.

2.2. Methodology

To meet the research objectives, the spatial data used in the research were:

1. Shapefile of the Ilo-Moquegua hydrographic basin developed by the National Water Authority at a scale of 1/100,000 [29].
2. Manual delimitation of the Ilo-Moquegua Hydrographic Basin based on 07 national charts at a scale of 1/100,000 from the National Geographic Institute [30].
3. 4,855 control points within the manual delimitation of the Ilo-Moquegua hydrographic basin located on the national maps at a scale of 1/25,000 of the National Geographic Institute[31].
4. Semi-automatic delimitation of the Ilo-Moquegua basin with data from the digital elevation model of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) downloaded from https://earthexplorer.usgs.gov/.
5. Semi-automatic delimitation of the Ilo-Moquegua basin with data from the digital elevation model of the Shuttle Radar Topography Mission (SRTM) downloaded from https://earthexplorer.usgs.gov/.
6. Semi-automatic delimitation of the Ilo-Moquegua basin with data from the digital elevation model ALOS Phased Array type L-band Synthetic Aperture Radar (ALOS PALSAR) downloaded from https://search.asf.alaska.edu/#/.

The semi-automatic delimitations of the Ilo-Moquegua hydrographic basin were carried out with the Arc Hydro Tools geoprocessing tool (ESRI, 2019) and corroborated with the HEC-GeoHMS geoprocessing tool [32], the same that were installed in ArcGIS 10.5 software.

The methodology for evaluating the cartographic products resulting from the digital elevation model ASTER, SRTM and ALOS PALSAR and determining which one is more realistic to the representation of the terrain of the Ilo-Moquegua hydrographic basin was applying the National positional accuracy standards Map Accuracy Standard (NMAS), Engineering Map Accuracy Standard (EMAS) and National Standard for Spatial Data Accuracy (NSSDA), which with greater detail of the comparison method, positional component, accuracy standard, description and procedure, are in the "Guide for the evaluation of the positional accuracy of spatial data” published by the Pan American Institute of Geography and History – PAIGH [33]. The PAIGH is a scientific and technical organization of the Organization of American States (OAS) responsible for generating and transferring specialized knowledge in the member states' cartography, geography, history and geophysics.

Positional Accuracy Standards

1. NMAS (National Map Accuracy Standard)
   - Scales smaller than 1:20,000: Horizontal accuracy requires that at least 90% of well-defined control points be within 1/30 of an inch of the map.
   - Scales of 1:20,000 or greater: Horizontal accuracy requires that at least 90% of control points be within 1/50 of an inch of the map.
   - Vertical accuracy requires that at least 90% of the elevations be within half of the map's contour interval.

2. EMAS (Engineering Map Accuracy Standard)
It is a more rigorous standard than NMAS; that is, EMAS must meet requirements according to the scale of representation. Perform a compliance test with the standard to determine if the mean error is acceptable, according to the value of the student’s t distribution, with n-1 degrees of freedom. Subsequently, compliance with the standard is performed to determine if the sample standard deviation is within acceptable limits. A test on the variance is performed by applying the Chi-square distribution with n-1 degrees of freedom.

3. NSSDA (National Standard for Spatial Data Accuracy)
   - This standard establishes that the positional accuracy of the data must be statistically valid, and each component's root mean square error must be calculated.
   - For elevation data, the vertical mean square error (elevation accuracy) should be reported.
   - Accuracy is reported in terms of the 95% confidence level standard deviation.

Validation of DEMs

NMAS: We can calculate the proportion of control points within the specified accuracy tolerances and verify whether it meets the required 90%.

EMAS: Depending on the specific project or jurisdiction, this may require additional specifications.

NSSDA: We can calculate and report the vertical mean square error of the DEMs relative to the control points and verify if it meets the project or application requirements.

Application of Artificial Intelligence in the evaluation and validation of DEMs

For the evaluation of positional accuracy and statistical validation of the digital terrain elevation models that delimited the Ilo-Moquegua hydrographic basin, the advanced GPT-4 artificial intelligence technology was applied, allowing for shortening processes and the use of various software for analysis and representation, a graphic of the results in each of the methodological stages that we describe:

1. For the evaluation of the DEMs that delimited the Ilo-Moquegua hydrographic basin, the ASTER, SRTM and ALOS PALSAR files are uploaded to ChatGPT 4 in

raster format (*.tif) compressed in a *.zip folder; also the 4 855 altimetric control points in vector format (*.shp) compressed in another *.zip folder.

2. ChatGPT 4 is then asked to extract the height values of the DEMs (ASTER, SRTM and ALOS PALSAR).
3. When ChatGPT 4, you are asked to send the extracted values to Microsoft Excel *.xls format.
4. We train Chat GPT 4 to apply the NMAS, EMAS and NSSDA positional accuracy standards.
5. We ask ChatGPT 4 to perform the spatial analysis of the SRTM, ASTER and ALOS PALSAR DEMs with the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) metrics.
1. We will proceed with the following statistical analyses:
6. Correlation: we will calculate the Pearson correlation coefficient between the elevations of the control points and the elevations extracted from the DEMs. This coefficient varies between -1 and 1, where 1 indicates a perfect positive correlation, -1 is a perfect negative correlation, and 0 is no correlation.
7. Coefficient of Determination: This is the square of the correlation coefficient and represents the proportion of the variance in the observed elevations that is predictable from the DEM elevations.
2. There is a difference between 0 and 1, where 1 indicates that the model explains all of the variability in the observed data, and 0 indicates that the model explains none.
8. Bland-Altman Plot: This graph analyses the agreement between two measurement methods. In this case, we will compare the control points' elevations with the DEMs' elevations. The x-axis shows the average of the two measurements, and the y-axis shows the difference between them. Lines of agreement and limits of agreement (mean of differences ± 1.96 standard deviations of differences) are also plotted to help interpret the deal.

RESULTS AND DISCUSSION

For the validation of the cartographic products resulting from the digital elevation model ASTER, SRTM and ALOS PALSAR, in terms of horizontal positional accuracy, they comply because we are working as a final product of the maps at a scale of 1/60,000, calculated from of the pixel resolution founded by [34]; where the map scale is equal to the raster resolution * 2 * 1000; In our study, the ASTER and SRTM DEMs have a resolution of 30 meters and all the DEMS are georeferenced to WGS 84. Therefore, the validation results refer to the vertical positional accuracy. NMAS-based DEM validation at a 1:60,000 scale considers the error tolerance for NMAS to typically allow 90% of control points to be within 1/30 of an inch on the map. , when it comes to vertical accuracy (altitude/elevation).

Terrain Tolerance (inches) =(1/30 inch on map) x 60,000

Converting to metric units, it is 50.8 meters. The validation of this tolerance is seen in table 1:

Table 1. Validation of DEMs based on NMAS

DEM	Proportion Within Tolerance	NMAS Compliance

SRTM	99,42 %	True
ALOS PALSAR	93,33 %	True
ASTER	99,36 %	True

All DEMs (SRTM, AlosPalsar, and ASTER) comply with the NMAS standard for a scale of 1:60,000 since more than 90% of the control points are within the allowed error tolerance. Notably, all DEMs show a high proportion of points within tolerance, indicating good conformity with the control points regarding vertical positional accuracy.

The validation of the DEMs based on the EMAS with a representation scale of 1:60,000, therefore:

Terrain Tolerance (inches) = (1/100 inch on map) x 60,000

Converting to metric units, it is 15,24 meters. The validation of this tolerance is seen in Table 2:

Table 2. Validation of DEMs based on EMAS

DEM	Proportion Within Tolerance	EMAS Compliance
SRTM	94,13 %	True
ALOS PALSAR	0,93 %	False
ASTER	97,68 %	False

These results indicate that, regarding vertical positional accuracy relative to control points, the SRTM DEM is the most compliant with the EMAS standard at this scale and tolerance, while AlosPalsar and ASTER are not.

The validation of the DEMs based on the EMAS with a representation scale of 1:60 000, so the error at the 95% confidence level (E95%) can be calculated by multiplying the RMSE by a factor derived from the normal distribution (approximately 1.96 for 95% confidence):

E95% = 1.96 x RMSE

The DEM validation based on the NSSDA shows the Root Mean Square Error (RMSE) and the 95% confidence level ($E_{95\%}$) error for each DEM compared to the control points in Table 3.

Table 3. Validation of DEMs based on NSSDA

DEM	RMSE (m)	$E_{95\%}$ (m)
SRTM	10.11	19.82
ALOS PALSAR	40.13	78.66
ASTER	11.41	22.37

SRTM and ASTER have the lowest errors in terms of RMSE and E95%, indicating that they are more accurate than ALOS PALSAR.

ALOS PALSAR has significantly higher errors, suggesting it may have lower vertical positional accuracy than the other two DEMs.

The results of the statistical analysis are seen in Fig. 2, Fig. 3 and Table 4:

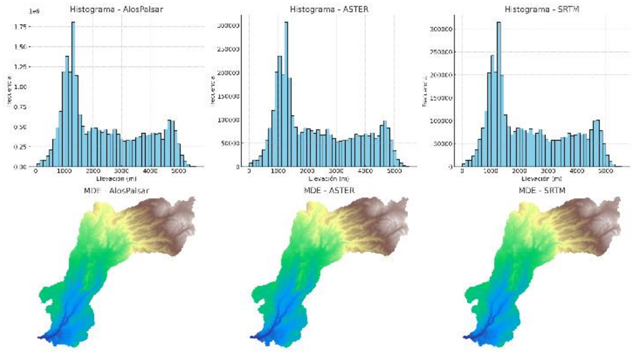

Fig. 2. Histograms represent the distribution of elevation values for each Digital Elevation Model (DEM): AlosPalsar, ASTER and SRTM.

Histograms clearly show how elevation values are distributed in each DEM and allow you to identify modes, ranges, and possible anomalies in the data.

AlosPalsar: The elevation distribution has a pronounced peak in the 2000-2500 m range, indicating a predominant elevation.

ASTER: The distribution is relatively flat, which could indicate a more uniform representation of different elevation classes.

SRTM: Similar to AlosPalsar, but with a slightly different shape, indicating differences in how each MDE represents the Earth's surface.

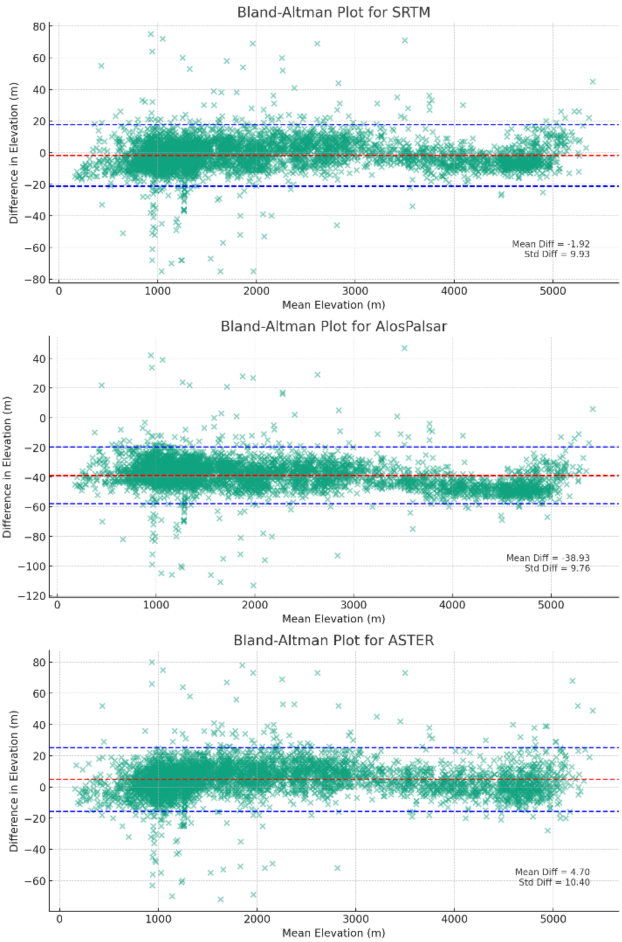

Fig. 3. Bland–Altman Plot

Table 4. Statistical validation results

DEM	Correlation	R^2
SRTM	0.999970	0.999940
ALOS PALSAR	0.999973	0.999947
ASTER	0.999967	0.999934

Correlation and R^2

All DEMs (SRTM, AlosPalsar, and ASTER) have a correlation and R^2 extremely high with the control points, indicating that the elevations of the DEMs are very strongly related to the observed elevations and explain a very high proportion of the variability in the observed elevations.

In the Bland-Altman plots, the dashed red lines represent the average differences between the observed and predicted elevations. If this line is close to zero, it indicates that, on average, the predictions are accurate.

The dashed blue lines represent the limits of agreement, which are the mean of the differences ± 1.96 times the standard deviation of the differences. Most differences (about 95% if the differences are typically distributed) should be within these limits.

CONCLUSION

The research determines the best digital elevation model for the Ilo-Moquegua hydrographic basin area. Firstly, given the larger scale, SRTM could be a viable option, especially in areas requiring less detail. Its RMSE and E95% are relatively low, indicating an acceptable level of positional accuracy. Secondly, similar to SRTM, it could be considered in areas where fine details are not critical, but additional validations should be considered. Thirdly, this DEM generally did not meet standards in our analyses, and therefore, caution should be exercised if it is considered for use. Fourthly, regardless of the DEM you choose, it is always advisable to perform additional validations, especially in critical areas for your project. Fifthly, in some cases, practitioners combine multiple DEMs to leverage each other's strengths and mitigate weaknesses. This might be a strategy to consider depending on your project. Sixthly, the correlation and R2 revealed a solid relationship and a high degree of explanation for the variability of the elevations observed by the MDEs. The Bland-Altman plots confirmed the agreement between the elevations predicted by the MDEs and those observed at the control points. Seventhly, this study highlights the importance and value of combining artificial intelligence techniques with statistical validation methods and positional accuracy standards to ensure the accuracy and reliability of EDMs in hydrological applications.

References

[1] E. Conde López, E. Salete Casino, J. Flores Escribano, and A. Vargas Ureña, "Application of Finite Element Method to Create a Digital Elevation Model," Mathematics, vol. 11, no. 6, pp. 1–16, 2023, doi: 10.3390/math11061522.

[2] S. Salekin, P. Lad, J. Morgenroth, Y. Dickinson, and D. F. Meason, "Uncertainty in primary and secondary topographic attributes caused by digital elevation model spatial resolution," Catena, vol. 231, no. April, p. 107320, 2023, doi: 10.1016/j.catena.2023.107320.

[3] C. J. Okolie and J. L. Smit, "A systematic review and meta-analysis of Digital elevation model (DEM) fusion: pre-processing, methods and applications," ISPRS Journal of Photogrammetry and Remote Sensing, vol. 188, no. April. Elsevier B.V., pp. 1–29, 2022. doi: 10.1016/j.isprsjprs.2022.03.016.

[4] D. Meseret et al., "Science of the Total Environment How does the choice of DEMs affect catchment hydrological modelling ?" vol. 892, no. May, 2023, doi: 10.1016/j.scitotenv.2023.164627.

[5] M. Martim de Moura, S. Beskow, F. da Silva Terra, C. Rogério de Mello, Z. Almeida da Cunha, and F. Cassalho, "Evaluation of geomorphological approaches combined with digital elevation models for the Nash's instantaneous unit hydrograph," J. South Am. Earth Sci., vol. 107, no. December 2020, 2021, doi: 10.1016/j.jsames.2020.103153.

[6] J. J. Durón Díaz, "El uso de modelos digitales de elevación y ortoimágenes para la determinación de los cauces de cuencas hidrológicas de la zona de Tixtla, Guerrero," Rev. Geográfica, no. 155, pp. 93–109, Aug. 2019, doi: 10.35424/regeo.v0i155.322.

[7] K. N. Ficher, D. D. R. Pereira, J. S. Oliveira, A. Q. de Almeida, and E. M. Uliana,

"Assessment of digital elevation models to obtain morphometric characteristics in the relief transition region," Ambient. e Agua - An Interdiscip. J. Appl. Sci., vol. 14, no. 1, p. 1, Jan. 2019, doi: 10.4136/ambi-agua.2280.
[8] G. C. Almeida, A. A. de A. Montenegro, A. A. Carvalho, V. R. Lourenço, T. A. B. Almeida, and M. J. Silva, "Morphometric characterization of the Alto do Ipojuca hydrographic basin," J. Hyperspectral Remote Sens., vol. 12, no. 3, p. 99, 2022, doi 10.29150/2237-2202.2022.251977.
[9] A. J. Ortíz-Rodríguez, C. Muñoz-Robles, J. G. Rodríguez-Herrera, V. Osorio-Carmona, and E. Barbosa-Briones, "Effect of DEM resolution on assessing hydrological connectivity in tropical and semi-arid basins of central Mexico," J. Hydrol., vol. 612, no. February 2022, doi: 10.1016/j.jhydrol.2022.128104.
[10] D. C. L. Alves, J. Weschenfelder, M. Ferreira-Cravo, J. M. de A. Espinoza, and M. da G. Albuquerque, "Advances in the application of Digital Elevation Models (DEMs) for the evaluation of coastal flooding," Mercator, vol. 20, pp. 1–19, 2021.
[11] L. Elsonbaty, H. E. D. Fawzy, H. M. Moghazy, G. Rashed, and M. Hamed, "Vertical accuracy assessment for open-source digital elevation models using GPS control points and watershed basins delineation using GIS," Alexandria Eng. J., vol. 84, no. November, pp. 47–58, 2023, doi: 10.1016/j.aej.2023.11.005.
[12] N. C. Sena, G. V. Veloso, E. I. Fernandes-Filho, M. R. Francelino, and C. E. G. R. Schaefer, "Analysis of terrain attributes in different spatial resolutions for digital soil mapping application in southeastern Brazil," Geoderma Reg., vol. 21, p. e00268, Jun. 2020, doi: 10.1016/J.GEODRS.2020.E00268.
[13] G. Popandopulo, S. Illarionova, D. Shadrin, K. Evteeva, N. Sotiriadi, and E. Burnaev, "Flood Extent and Volume Estimation Using Remote Sensing Data," Remote Sens., vol. 15, no. 18, p. 4463, 2023, doi: 10.3390/rs15184463.
[14] W. Zhang, B. Hu, Y. Liu, X. Zhang, and Z. Li, "Urban Flood Risk Assessment through the Integration of Natural and Human Resilience Based on Machine Learning Models," Remote Sens., vol. 15, no. 14, 2023, doi: 10.3390/rs15143678.
[15] M. Mohammadi, A. K. Darvishan, V. Spalevic, B. Dudic, and P. Billi, "Analysis of the impact of land use changes on soil erosion intensity and sediment yield using the intro model in the Talar watershed of Iran," Water (Switzerland), vol. 13, no. 6, pp. 1–15, 2021, doi: 10.3390/w13060881.
[16] S. Nouwakpo, C. Huang, L. Bowling, P. Owens, and M. Weltz, "Microtopography Changes on a Laboratory Hillslope," pp. 1–14, 2021.
[17] T. Chaithong, "Flash Flood Susceptibility Assessment Based on Morphometric Aspects and Hydrological Approaches in the Pai River Basin, Mae Hong Son, Thailand," Water (Switzerland), vol. 14, no. 19, 2022, doi: 10.3390/w14193174.
[18] P. Costabile, C. Costanzo, C. Gandolfi, F. Gangi, and D. Masseroni, "Effects of DEM Depression Filling on River Drainage Patterns and Surface Runoff Generated by 2D Rain-on-Grid Scenarios," Water (Switzerland), vol. 14, no. 7, 2022, doi: 10.3390/w14070997.
[19] S. L. K. Unnithan, B. Biswal, W. Sharples, C. Rüdiger, K. Bahramian, and J. Hou, "Sensitivity Analysis of Modelled Flood Inundation Extents over Hawkesbury–Nepean Catchment," Geosci., vol. 13, no. 3, 2023, doi: 10.3390/geosciences13030067.
[20] P. Preeti, Y. Shendryk, and A. Rahman, "Identification of Suitable Sites Using GIS for Rainwater Harvesting Structures to Meet Irrigation Demand," Water (Switzerland), vol. 14, no. 21, pp. 1–17, 2022, doi: 10.3390/w14213480.
[21] E. Penfound and E. Vaz, "Analysis of wetland landcover change in great lakes urban areas using self-organizing maps," Remote Sens., vol. 13, no. 24, 2021, doi: 10.3390/rs13244960.
[22] A. J. Rummell et al., "Watching the Saltmarsh Grow: A High-Resolution Remote Sensing Approach to Quantify the Effects of Wetland Restoration," Remote Sens., vol. 14, no. 18,

2022, doi: 10.3390/rs14184559.

[23] E. F. Escalante, J. D. H. Casas, C. M. de G. Per, M. D. M. Vera, and C. M. Valverde, "Unintentional Recharge of Aquifers from Small Dams and Dykes in Spain: A GIS-Based Approach to Determine a Fractional Volume," Earth, vol. 4, no. 3, pp. 584–605, 2023, doi: 10.3390/earth4030031.

[24] I. Ki, H. Chakroun, Y. Koussoube, and K. Zouari, "Assessment of Aquifer Recharge Potential Using Remote Sensing, GIS and the Analytical Hierarchy Process (AHP) Combined with Hydrochemical and Isotope Data (Tamassari Basin, Burkina Faso)," Water (Switzerland), vol. 15, no. 4, 2023, doi: 10.3390/w15040650.

[25] L. Shi, J. Fang, and Y. Zhao, "Automatic shadow detection in high-resolution multispectral remote sensing images," Comput. Electr. Eng., vol. 105, no. December 2022, p. 108557, 2023, doi: 10.1016/j.compeleceng.2022.108557.

[26] D. Tibebe, M. A. Degefu, W. Bewket, E. Teferi, G. O'Donnell, and C. Walsh, "Homogenous Climatic Regions for Targeting Green Water Management Technologies in the Abbay Basin, Ethiopia," Climate, vol. 11, no. 10, 2023, doi: 10.3390/cli11100212.

[27] J. Li and D. W. S. Wong, "Effects of DEM sources on hydrologic applications," Comput. Environ. Urban Syst., vol. 34, no. 3, pp. 251–261, 2010, doi: 10.1016/j.compenvurbsys.2009.11.002.

[28] S. Sarasamma et al., "Nanoplastics cause neurobehavioral impairments, reproductive and oxidative damages, and biomarker responses in zebrafish: Throwing up alarms of widespread health risk of exposure," Int. J. Mol. Sci., vol. 21, no. 4, Feb. 2020, doi: 10.3390/ijms21041410.

[29] ANA, "Demarcación y delimitación de las autoridades administrativas del agua," Lima, 2009. Accessed: Jan. 26, 2019. [Online]. Available: http://repositorio.ana.gob.pe/handle/ANA/213

[30] M. de E. MED, "Descarga de información espacial del MED," 2015. https://sigmed.minedu.gob.pe/descargas/ (accessed May 22, 2023).

[31] I. G. N. IGN, "CATÁLOGO DE METADATOS DE DATOS FUNDAMENTALES," Catálogo de metadatos, 2021. https://portalgeo.idep.gob.pe:8443/geonetwork/srv/spa/catalog.search#/home (accessed Aug. 08, 2021).

[32] US Army Corps of Engineers, "Hydrologic Engineering Center Software," Hydrologic Engineering Center Software, 2021. https://www.hec.usace.army.mil/software/default.aspx (accessed Aug. 08, 2021).

[33] F. J. Ariza-López, J. L. García-Balboa, J. Rodríguez-Avi, and J. Robledo, Guía para la evaluación de la exactitud posicional de datos espaciales. Ciudad de México, México, 2019.

[34] W. Tobler, "Measuring spatial resolution," Proceedings, L. Resour. Inf. Syst. Conf., pp. 12–16, Jan. 1987.