Comparative Evaluation of Image Compression Techniques for High-Resolution Orthophoto Imagery

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KEYWORDS

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ABSTRACT

The rapid growth of high-resolution data from UAV, LiDAR, and satellite platforms has significantly improved the accuracy and applicability of geospatial analysis, while simultaneously creating challenges related to large data volumes, storage, transmission, and computational efficiency. Image compression plays a critical role in addressing these challenges by reducing data size while maintaining acceptable visual and analytical quality. This study presents a comparative analysis of three widely used image compression techniques—JPEG2000 (lossless and lossy) and Enhanced Compression Wavelet (ECW)—applied to high-resolution LiDAR orthophotos. Compression performance was evaluated in terms of output size, compression ratio, and processing time, while image quality was assessed through both qualitative parameters (edge sharpness, spatial detail, color fidelity, radiometric consistency, texture, and geometric integrity) across multiple interpretation scales and quantitative approaches (MSSSIM, PSNR, ERGAS, and RASE metrics). Results indicate that JPEG2000 lossless preserves complete radiometric and spatial fidelity, making it ideal for high-precision analytical applications, although it offers limited compression efficiency. JPEG2000 lossy demonstrates the best overall balance, achieving high compression ratios with lower processing time while maintaining strong structural and spectral integrity, as evidenced by consistently high MSSSIM and PSNR values and low error metrics. In contrast, ECW achieves the highest compression ratios and smallest file sizes, making it highly efficient for storage and transmission; however, it exhibits greater variability, higher computational cost, and reduced performance in high-detail features. Overall, JPEG2000 lossy emerges as the most suitable compression method for general remote sensing applications, while JPEG2000 lossless is recommended for high-accuracy tasks and ECW for storage-efficient visualization and data dissemination.

1. INTRODUCTION

The rapid advancement of remote sensing technologies has led to an unprecedented increase in the availability of high-resolution geospatial data. Improvements in satellite sensors, Light Detection and Ranging (LiDAR) systems, and Unmanned Aerial Vehicle (UAV) platforms have enabled the acquisition of imagery with spatial resolutions ranging from sub-meter to centimeter levels (Yao et al., 2019; Dong & Chen, 2017). As a result, geospatial analysis has become more precise and reliable, significantly enhancing applications in topographic mapping, urban planning, disaster management, and environmental monitoring. The growing demand for accurate, large-scale, and frequently updated spatial information has further accelerated the adoption of high-resolution datasets in both scientific research and operational practices.

Digital image processing plays a central role in extracting meaningful information from high-resolution geospatial datasets in Nepal. Fundamental techniques—including image enhancement, filtering, segmentation, feature extraction, and classification—are essential for transforming raw sensor data into usable geospatial products (Schowengerdt, 2012). In the context of Nepal, high-resolution orthophotos derived from UAV and LiDAR platforms have become increasingly important for large-scale mapping, cadastral updating, infrastructure planning, and disaster risk assessment. These geometrically corrected images remove distortions caused by rugged terrain, sensor tilt, and perspective effects, thereby ensuring uniform scale and enabling accurate map-based measurements (Sestras et al., 2025). However, Nepal's highly heterogeneous landscape—characterized by steep topography, fragmented land parcels, mixed land cover, and rapid urban expansion—poses significant challenges for automated image classification. As a result, visual interpretation continues to be the primary method for feature extraction in many operational applications. Even where automated approaches are applied, extensive manual validation and editing are required to achieve the level of accuracy demanded by national mapping and land administration activities.

Despite the widespread use of high-resolution datasets across various domains, they also introduce significant challenges related to data volume. Large file sizes increase the burden on storage systems, transmission bandwidth, and computational resources, particularly for institutions with limited infrastructure. These constraints can hinder efficient data sharing, processing, and long-term management. To address these challenges, image compression has become an essential component of geospatial data handling. Compression techniques reduce data size while attempting to preserve the visual and analytical quality required for specific applications. In remote sensing workflows, effective compression enables faster data transfer, reduces storage costs, and supports web-based and cloud-enabled geospatial services.

Image compression methods are broadly categorized into lossless and lossy approaches. Lossless compression ensures exact reconstruction of the original data but typically achieves limited reduction in file size. In contrast, lossy compression attains significantly higher compression ratios by removing redundant or less perceptually important information, albeit at the cost of some data degradation (Singh et al., 2016). Given the increasing reliance on high-resolution orthophotos for both visual interpretation and analytical tasks, it is essential to evaluate how different compression techniques affect image quality and usability.

Therefore, the primary objective of this study is to comparative evaluate the performance of commonly used image compression techniques for high-resolution LiDAR orthophotos, with a focus on balancing compression efficiency, radiometric integrity, and visual interpretability for geospatial applications.

2. IMAGE COMPRESSION TECHNIQUES

Image compression techniques are generally classified into lossless and lossy methods, based on whether the original image can be perfectly reconstructed after decompression. Lossless compression preserves all original pixel values. In contrast, lossy compression reduces file size by eliminating perceptually or statistically redundant information. Although this approach introduces some level of data loss, it significantly decreases storage and transmission requirements. (Singh et al., 2016).

Common lossless algorithms include Run-Length Encoding (RLE), Lempel–Ziv–Welch (LZW), Deflate (ZIP-based compression), and JPEG 2000 operating in lossless mode (Gupta et al., 2017). RLE is particularly effective for images containing large homogeneous regions, while LZW is widely implemented in TIFF formats. Deflate is commonly used in PNG and other ZIP-based formats. JPEG 2000 in lossless mode employs reversible wavelet transforms, enabling higher compression efficiency compared to traditional lossless techniques. Although lossless methods typically achieve lower compression ratios than lossy approaches, they guarantee complete preservation of the original data.

For lossy compression, widely used algorithms include the Discrete Cosine Transform (DCT) and the Discrete Wavelet Transform (DWT). DCT forms the basis of standard JPEG compression, whereas DWT underpins JPEG 2000 lossy compression and ECW format (Gautam, 2010). These methods achieve higher compression ratios by reducing data precision and removing redundancy; however, excessive compression can introduce artifacts and degrade both spatial and spectral information. Consequently, selecting an appropriate compression method requires careful consideration of the trade-off between file size reduction and data quality.

1.1 JPEG 2000

JPEG 2000 (ISO/IEC 15444) is an international image compression standard based on wavelet transform coding, designed to deliver high compression efficiency, scalability, and both lossless and lossy encoding (Marcellin et al., 2000). It is widely used in remote sensing and geospatial applications for preserving spatial detail, handling large raster datasets, and integrating georeferencing and metadata within the file. The standard employs the Discrete Wavelet Transform (DWT) to decompose images into multi-resolution frequency sub-bands, followed by Embedded Block Coding with Optimized Truncation (EBCOT), which combines quantization and context-based arithmetic coding (Rabbani & Joshi, 2002). This enables efficient compression, precise rate control, and progressive reconstruction by quality or resolution. In lossy mode, irreversible wavelet filters and quantization achieve high compression while maintaining visual quality, whereas lossless mode uses reversible integer transforms without quantization to allow exact image reconstruction and full radiometric preservation (Rabbani & Joshi, 2002).

1.2 Enhanced Compression Wavelet (ECW)

Enhanced Compression Wavelet (ECW) is a proprietary wavelet-based raster compression format developed by Hexagon for efficient storage, transmission, and visualization of large geospatial datasets, including orthophotos, satellite imagery, and digital elevation models (Hexagon, 2025). ECW supports rapid visualization at different spatial scales without fully decompressing the file and thus, addresses the challenges of big geospatial data by offering high compression ratios, fast access, and flexible data handling. ECW uses DWT to decompose images into frequency sub-bands, separating low-frequency components that capture overall structure from high-frequency components that encode fine details such as edges and textures (Demirel & Anbarjafari, 2011). The wavelet coefficients are then quantified and entropy-coded, where the quantization level determines the compression ratio and balances file size against radiometric fidelity. ECW files retain embedded georeferencing and projection metadata, including coordinate reference system (CRS), pixel resolution, and spatial extents, enabling seamless integration into GIS workflows and preserving spatial alignment with other raster or vector layers without requiring auxiliary world files.

3. METHODOLOGY

3.1 Image datasets

For this study, orthomosaic imagery with a ground sampling distance (GSD) of 15 cm produced by the Survey Department under the LiDAR Surveying and Mapping Program (2022) was used (Joshi & Koirala, 2020). A total of 67 RGB orthoimage tiles were acquired in GeoTIFF format. The orthophotos had been preprocessed as part of the original mapping project and provided as color-balanced mosaics. They were orthorectified using a high-resolution digital elevation model (DEM) generated from the LiDAR project, ensuring minimal geometric distortion and radiometric inconsistencies. As a result, the dataset is readily usable for downstream analysis without the need for additional photogrammetric correction or image enhancement.

3.2 Compression formats and platforms

For this study, two widely used wavelet-based image compression formats were applied to the LiDAR-orthophotos. ECW compression was performed using ERDAS IMAGINE, which supports efficient handling of large, high-resolution geospatial datasets and provides progressive, multi-resolution access. JPEG 2000 was implemented in a GIS environment, applying both lossless and lossy modes to evaluate the trade-off between compression ratio and data fidelity. The choice of these platforms allowed direct comparison of commonly used remote sensing compression workflows under realistic operational conditions, reflecting typical data processing and analysis scenarios in geospatial applications.

3.3 Experimental setup

All image compression processes were carried out on a computing system equipped with Intel(R) Xeon(R) W-2145 CPU operating at 3.70GHz, 64 GB of RAM and 2 GB AMD graphics card.

3.4 Evaluation of compression performance and compressed images

The evaluation of compression performance and the quality of compressed images was carried out using a combination of computational performance analysis, qualitative visual assessment, and quantitative statistical metrics, ensuring a comprehensive and multi-dimensional comparison of the applied compression techniques (JPEG2000 lossless, JPEG2000 lossy, and ECW).

For compression performance analysis, key indicators including compressed file size, compression ratio, and processing time were measured for each dataset. The compressed output size was compared against the original input to assess storage efficiency, while the compression ratio was calculated to quantify the degree of data reduction achieved by each method. Additionally, compression time was recorded to evaluate computational efficiency and processing overhead. These metrics were analyzed comparatively across all test images to identify trade-offs between storage optimization and processing requirements.

The qualitative assessment focused on evaluating the perceptual and interpretative quality of the compressed images. Key parameters assessed included edge sharpness, spatial detail preservation, color fidelity, radiometric consistency, texture representation, and geometric integrity. Representative features such as building edges, roads, vegetation, water bodies, and small urban objects were examined to understand how compression affects both high-detail and homogeneous regions. Evaluation was performed using a matrix of representative image clips from both the original and compressed datasets, enabling side-by-side visual comparison.

For quantitative assessment, widely recognized image quality metrics were employed to objectively evaluate the fidelity of compressed images relative to the original datasets. These included Multi-Scale Structural Similarity Index (MSSSIM), Relative Average Spectral Error (RASE), Peak Signal-to-Noise Ratio (PSNR), and Erreur Relative Globale Adimensionnelle de Synthèse (ERGAS) (Table 1). Furthermore, statistical analysis was performed to assess central tendencies, variability, and robustness of each compression method.

4. RESULTS AND ANALYSIS

4.1 Compression performance analysis

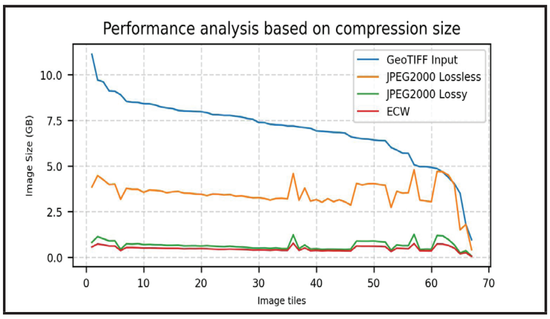


Figure 1: Input vs output compressed size (JPEG2000 lossless vs JPEG2000 lossy vs ECW)

The comparative evaluation of JPEG2000 lossless, JPEG2000 lossy, and ECW compression techniques in terms of compressed output file size (in Figure 1) demonstrates that ECW consistently achieved the highest compression, compared to both JPEG2000 variants. JPEG2000 lossy provided compression near to ECW, while JPEG2000 lossless resulted in output sizes closer to the original input, as expected due to its non-destructive nature.

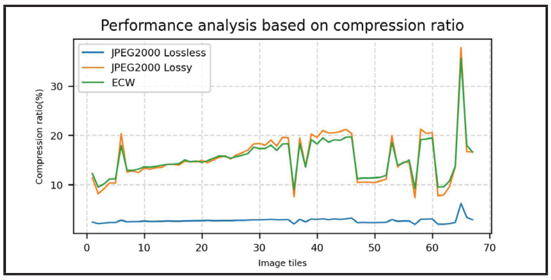


Figure 2: Compression ratio comparison among JPEG2000 lossless, JPEG2000 lossy, and ECW

Similarly, compression ratio analysis (in Figure 2) further reinforced these observations. ECW exhibited the highest compression ratios across most test images, followed by JPEG2000 lossy, while JPEG2000 lossless maintained relatively low and stable ratios. However, ECW also showed variability in performance, with occasional spikes in compression ratio for highly homogeneous images, indicating sensitivity to image content.

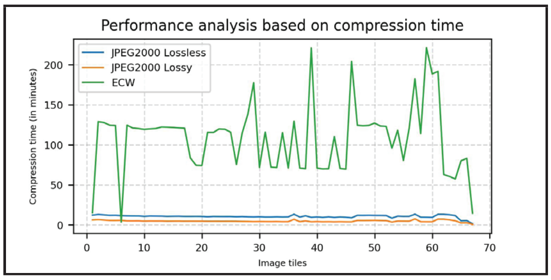


Figure 3: Compression time comparison among JPEG2000 lossless, JPEG2000 lossy, and ECW

In terms of computational performance (in Figure 3), JPEG2000 lossy demonstrated the most efficient balance between compression ratio and processing time, achieving relatively high compression at significantly lower processing times. JPEG2000 lossless exhibited moderate processing times with consistent behavior across datasets. In contrast, ECW required substantially higher compression times,

Table 1: Quantitative Evaluation Metrics with Variable Definitions

Metric	Formula	Notations	Measures	Value Range and interpretation
MSSSIM (Multi-Scale Structural Similarity)	$MSSSIM = [l_m(x,y)^{\alpha_M} . \prod_{j=1}^{M} [c_j(x,y)]^{\beta_j} [s_j(x,y)]$	x,y: reference and test images; M: number of scales; $l_m(x,y)$: luminance comparison at coarsest scale $c_j(x,y)$: contrast comparison at scale j; $s_j(x,y)$: structure comparison at scale j; $\alpha_M, \beta_j, \Upsilon_j$: weighting factors	Structural Similarity (perceptual quality)	Value range: 0-1 Interpretation: Higher is better
RASE (Relative Average Spectral Error)	$RASE = \frac{100}{\mu}\sqrt{\frac{1}{N}\sum_{i-1}^{N}(RMSE_i)^2}$	N: number of spectral bands;μ: mean radiance of all band; $RMSE_i$: root mean square error of band i	Spectral radiometric error	Value range:>= 0 Interpretation: Lower is better
PSNR (Peak Signal-to-Noise Ratio)	$PSNR = 20 * log_{10}\left(\frac{MAX}{\sqrt{MSE}}\right)$	MAX : maximum pixel value; MSE : Mean square error	Pixel error (signal fidelity)	Value range: 0 – inf (dB) Interpretation: higher is better
ERGAS (Erreur Relative Globale Adimensionnelle de Synthèse	$ERGAS = 100.\frac{h}{l}\sqrt{\frac{1}{N}\sum_{i-1}^{N}\left(\frac{RMSE_i}{\mu_i}\right)^2}$	h/l: resolution ratio; $RMSE_i$: RMSE of band i; μ_i: mean of band I; N : number of band	Global relative spectral error	Value range: >= 0 Interpretation: lower is better

particularly for large or complex images, indicating a higher computational overhead despite its superior compression efficiency.

Overall, the comparative evaluation of JPEG2000 lossless, lossy, and ECW compression techniques demonstrates clear tradeoffs between compression efficiency, processing time, and storage optimization.

4.2 Qualitative assessment

A qualitative evaluation was conducted to assess the perceptual impact of selected compression techniques across multiple spatial scales and feature types, including edge sharpness, spatial detail preservation, color fidelity, radiometric consistency, texture, and geometric integrity. The chosen scales follow established remote sensing principles that relate object size to spatial resolution for accurate feature interpretation (Lechner et al., 2009; Blaschke, 2010). The selection of interpretation scales was based on the relationship between feature size and spatial resolution, where smaller and more detailed features require larger scales to ensure accurate representation, while larger and homogeneous features can be effectively interpreted at smaller scales without significant loss of information.

The qualitative evaluation shows that lossless JPEG2000 compression preserves image quality almost identical to the original across all parameters, including edge sharpness, spatial detail, color fidelity, radiometric consistency, texture, and geometric integrity. In contrast, lossy JPEG2000 introduces slight blurring, minor detail loss, and subtle color shifts, while ECW lossy compression provides efficient storage but results in slight smoothing, reduced texture, and minor geometric distortions. High-detail features such as vehicles, building edges, and urban textures are relatively affected, whereas larger homogeneous features like vegetation and water bodies remain relatively stable. However, it is important to acknowledge that qualitative assessment is inherently limited by human visual perception and may not capture subtle pixel-level distortions relevant to automated analysis workflows.

4.3 Quantitative assessment

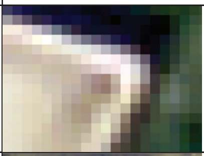
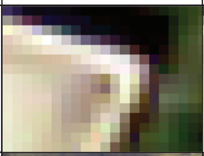
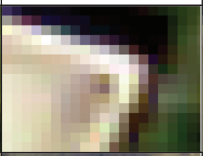
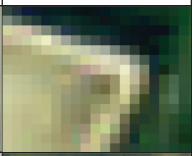
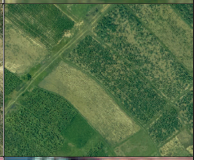
The comparative quantitative evaluation of compression performance using four widely used statistical analysis in image quality metrics – MSSSIM, RASE (%), PSNR (dB), and ERGAS reveals across three compression methods: JPEG2000 (lossless), JPEG2000 (lossy) and ECW. It is important to note that JPEG (lossless) consistently demonstrated perfect values for all images across all evaluated metrics; therefore, it was excluded from the boxplot analysis to avoid graphical saturation and preserve interpretability.

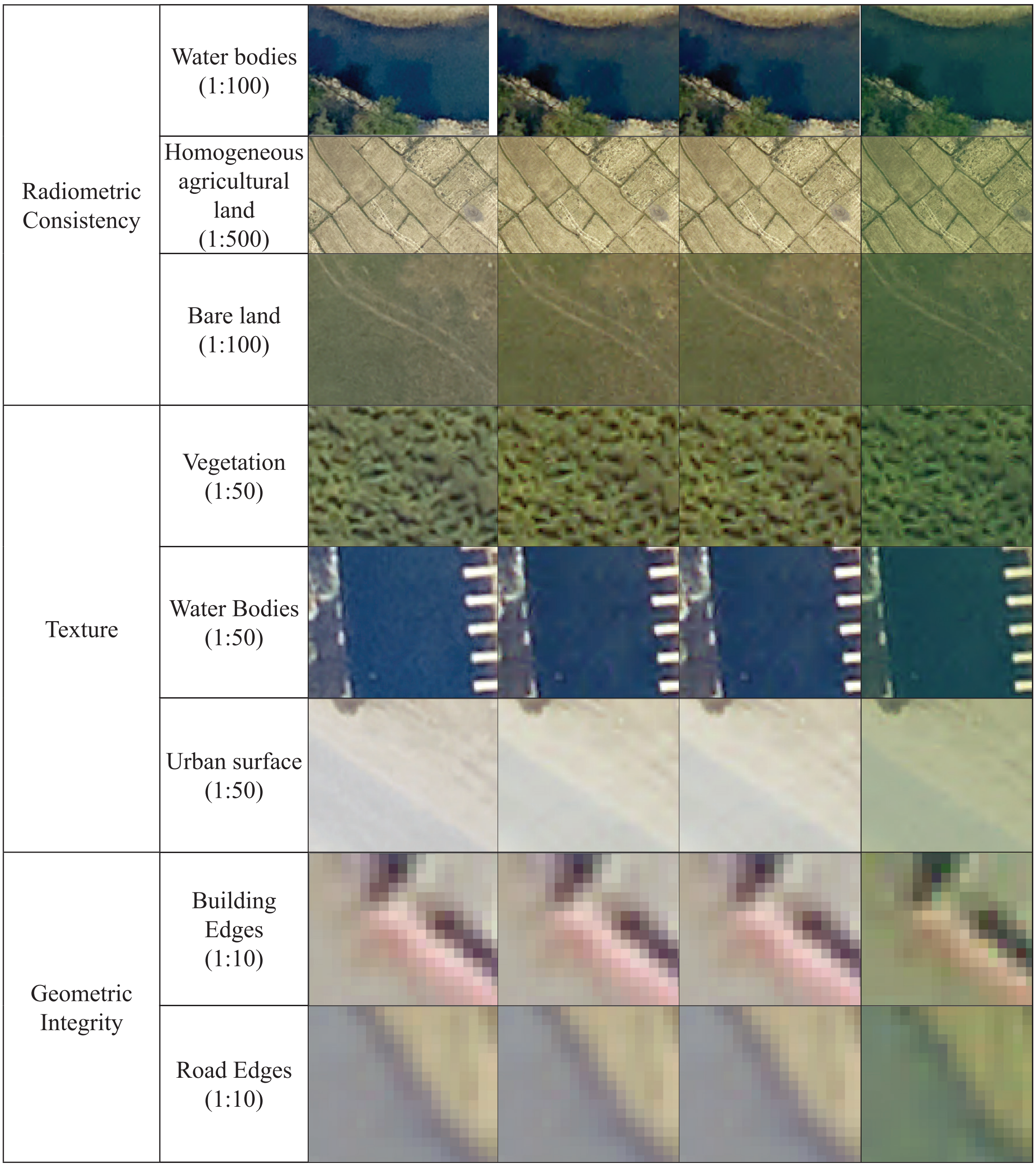
As illustrated in Figure. 4, Both JPEG (lossy) and ECW methods achieve high MSSSIM (>0.98), indicating strong structural preservation. However, JPEG2000 achieve slightly higher MSSSIM median values and exhibit a tighter IQR, indicating superior preservation of structural information and more consistent perceptual quality. However, few outlier exist for both cases.

In terms of spectral fidelity, JPEG2000 demonstrates lower median RASE values with a tighter interquartile range, whereas ECW exhibits greater dispersion and several high-value outliers (up to 7%), suggesting less consistent performance.

Similarly, PSNR results show that JPEG2000 generally attains higher reconstruction quality, with median values exceeding those of ECW and fewer low-quality outliers. The upper whisker for JPEG2000 extends beyond 40 dB, indicating excellent quality in best cases while

Table 2: Parameter-based qualitative evaluation of compression techniques (JPEG2000 lossless vs JPEG 2000 lossy vs ECW)

Key Parameters	**Description**	**Original Image**	**Lossless**	**Lossy**	
			JPEG2000	**JPEG2000**	**ECW**
Edge Sharpness	Building Boundaries (1:10)				
	Shoreline (water bodies) (1:100)				
	Road (1:100)				
Spatial Detail Preservation	Single tree crown (1:100)				
	Vehicles (1:50)				
	Small house (1:100)				
Color Fidelity	Vegetation (1:500)				
	Building roofs (1:50)				
	Roads (1:50)				



Radiometric Consistency	Water bodies (1:100)
	Homogeneous agricultural land (1:500)
	Bare land (1:100)
Texture	Vegetation (1:50)
	Water Bodies (1:50)
	Urban surface (1:50)
Geometric Integrity	Building Edges (1:10)
	Road Edges (1:10)

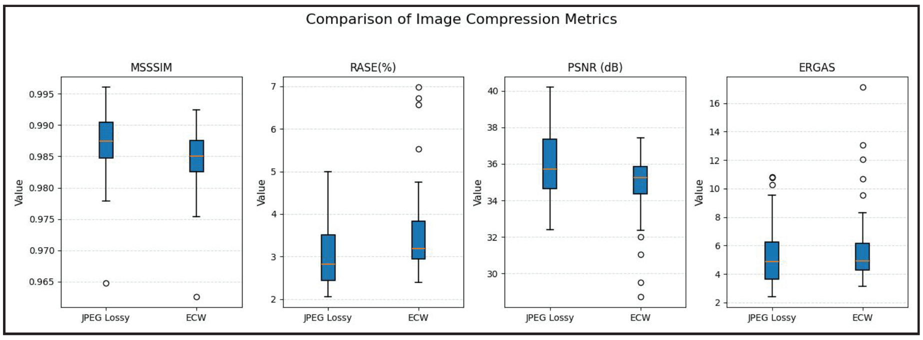


Figure 4: Boxplot for quantitative evaluation of compression techniques (JPEG2000 lossless vs JPEG 2000 lossy vs ECW

ECW shows more lower-end outliers (down to ~29 dB), suggesting occasional degradation.

For the ERGAS metric, although both methods present comparable central tendencies, ECW displays significantly higher variability and more extreme outliers (up to 17), indicating occasional degradation in global reconstruction accuracy.

Overall, JPEG2000 (lossy) not only provides better average performance across all evaluated metrics but also demonstrates greater robustness and stability, making it a more reliable choice for applications requiring high-fidelity image compression. However, ECW exhibits greater dispersion and more outliers, indicating less predictable performance.

5. DISCUSSION

The comparative assessment of JPEG2000 (lossless and lossy) and ECW compression methods highlights important trade-offs between compression efficiency, processing time, data fidelity and format interoperability, which directly influence their suitability for different remote sensing applications.

JPEG2000 lossless preserves original image quality and radiometric and spectral integrity, making it the most appropriate choice for high-precision tasks such as numerical analysis, automatic classification, and scientific studies. However, its lower compression efficiency limits its practicality for large-scale storage.

JPEG2000 lossy provides the best overall balance, achieving high compression ratios with low processing time while maintaining strong structural and spectral fidelity. Its consistent performance across MSSSIM, RASE, PSNR, and ERGAS metrics indicates that it is well-suited for a wide range of applications, including visual interpretation, numerical analysis, and automated classification.

ECW achieves the highest compression ratios and smallest file sizes, making it advantageous for data storage and transmission. ECW is more appropriate for visual interpretation, general visualization, and feature digitization, where storage efficiency and quick rendering are prioritized over fine analytical accuracy. However, its higher computational cost, low performance on high detailed features and greater variability and the presence of significant outliers across multiple metrics, along with observed smoothing and occasional distortions, reduce its reliability for detailed interpretation and analytical applications.

Overall, JPEG2000 lossy emerges as the most versatile option, offering a strong balance between compression efficiency, processing time, and data fidelity within an open and widely supported standard. JPEG2000 lossless remains essential for applications requiring complete data integrity, despite its lower compression efficiency. In contrast, although ECW provides superior compression and storage efficiency, it is a proprietary format with limited acceptance across image visualization and processing platforms, restricting its use in interoperable and analysis-driven workflows. Therefore, ECW is best suited for storage-efficient visualization and dissemination, while open-format JPEG2000 is preferable for analytical and cross-platform remote sensing applications.

These findings are largely consistent with existing literature, which generally recognizes JPEG2000 as a robust standard for remote sensing image and its product compression due to its superior rate-distortion performance and preservation of spectral fidelity (Ruzickova & Ruzicka, 2012; Zabala & Pons, 2010). Previous studies have demonstrated that lossless JPEG2000 maintains radiometric integrity for scientific applications, while its lossy variant achieves an effective balance between compression efficiency and image quality, particularly for classification and interpretation tasks (Zabala & Pons, 2010). Similarly, although ECW is known for achieving high compression ratios and efficient data streaming, prior research and technical documentation have reported smoothing effects and reduced reliability in representing fine spatial details under higher compression levels (Hexagon, 2025).

6. CONCLUSION AND RECOMMENDATION

This study aimed to evaluate the performance of JPEG2000 (lossless and lossy) and ECW compression techniques for high-resolution LiDAR-derived orthophotos using both qualitative and quantitative assessment methods. The results showed that ECW achieved the highest compression ratios and smallest file sizes, while JPEG2000 lossy provided comparable compression with significantly lower processing time. JPEG2000 lossless preserved image quality and radiometric integrity almost identical to the original but with limited compression efficiency. Quantitative analysis further indicated that JPEG2000 lossy consistently achieved higher structural similarity and signal quality with lower error metrics compared to ECW, while ECW exhibited greater variability and the presence of outliers.

These findings indicate that, although all three methods effectively reduce data volume, their performance differs in terms of efficiency, consistency, and quality preservation. For practical applications, JPEG2000 lossless is recommended for high-precision analytical tasks requiring full data integrity, JPEG2000 lossy for general-purpose remote sensing workflows requiring a balance between quality and efficiency, and ECW for storage-efficient visualization and data dissemination where maximum compression is prioritized over analytical accuracy. Therefore, the selection of a compression technique should be guided by application requirements, particularly in balancing storage efficiency and data fidelity in high-resolution remote sensing workflows.

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