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Bridging Satellite and UAV Technologies for High-Resolution Hydraulic Simulations: A Case Study in Iran's Marun Basin

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ABSTRACT

This study focuses on evaluating and comparing the effectiveness of high-resolution Digital Elevation Models (DEMs) derived from UAVs and satellite (ALOS) data for hydraulic simulations. Conducted in the Marun Basin in Iran, the research assesses the accuracy of these DEMs in modeling flood events using the HEC-RAS 2D simulation framework. By integrating rainfall data and streamflow measurements, the study underscores the potential of UAV-derived data for precision hydraulic modeling while exploring the utility of freely available satellite data for broader applications. This dual comparison offers valuable insights for flood management, especially in regions where precise data acquisition and timely response are critical.

Background and Objectives: Floods are one of the most significant natural disasters globally, causing substantial economic and human losses. Climate change exacerbates these risks. Central to flood simulations are Digital Elevation Models (DEMs), which provide the foundational data on terrain and topography. The study examines the capabilities of UAV-derived DEMs, known for their high spatial resolution, and ALOS satellite DEMs, which offer extensive coverage at a lower resolution. UAVs have revolutionized flood modeling by enabling precise data acquisition, especially in small, localized areas. In contrast, ALOS data is widely available, cost-effective, and better suited for large-scale applications. By employing both sources for 2D hydraulic modeling, the study provides a comprehensive evaluation of their strengths, limitations, and potential for integration.

Materials and Methods: The research was conducted in the Paskuhak region of Shiraz, Iran, encompassing a 4.3 km² section of the Marun watershed. Rainfall and streamflow data were collected using local gauges, while DEMs were derived from UAVs and ALOS satellite. The drone was used to capture high-resolution imagery. The data was processed to produce DEMs with a spatial resolution of 5 cm and a vertical accuracy of 2 cm. ALOS data, with a spatial resolution of 12.5 meters, was calibrated using UAV data to ensure comparability and reliability. The HEC-RAS 2D software was employed for hydraulic simulations. Precipitation was used

as the boundary condition, a novel approach compared to the traditional discharge-based boundary conditions. Calibration and validation of the model were performed using observed hydrographs, with Manning's roughness coefficient optimized for accuracy. Mesh sizes for the simulations were carefully selected to balance computational efficiency and result precision. A 2 m × 2 m mesh was used for the UAV DEM, while a 5 m × 5 m mesh was applied to the ALOS DEM.

Results: The UAV-derived DEMs outperformed ALOS DEMs in accurately representing terrain features. Their higher spatial resolution provided a more detailed and realistic depiction of channel meandering, slope variations, and floodplain characteristics. This precision translated into more accurate hydraulic simulations, particularly in predicting peak discharge and time-to-peak metrics. In terms of peak discharge, the UAV DEM estimated peak discharge within 0.85% of the data observed, while the ALOS DEM overestimated it by 5.2%. The UAV DEM's predictions were nearly identical to the observed data, whereas the ALOS DEM underestimated the time to peak by 8.6%. The UAV DEM consistently simulated lower maximum flood depths compared to the ALOS DEM, aligning more closely with real-world observations. For instance, the UAV DEM predicted depths 14.2% lower than the ALOS DEM on average. These differences highlight the superior ability of UAV data to capture fine-scale terrain details, which are essential for accurate flood depth estimation. The inclusion of rainfall as a boundary condition enhanced the dynamism and accuracy of simulations. This method contrasts with traditional practices that rely on discharge time series and demonstrated the potential to eliminate the need for separate hydrological studies. The rainfall-driven simulations provided a more comprehensive understanding of watershed response, contributing to improved predictive capabilities. Both UAV and ALOS DEMs produced hydrographs that closely matched observed data, with notable differences in peak intensity and timing. The UAV model, with its higher temporal resolution (6-minute intervals), captured rapid flow changes more effectively than the hourly interval data from hydrometric stations. This capability is particularly valuable for real-time flood forecasting and emergency response. Error metrics validated the superior accuracy of UAV-derived data so that Root Mean Square Error (RMSE) resulted in UAV (0.022) vs. ALOS (0.024) and Relative Error (RE) in Peak Discharge depicted UAV (10.9%) vs. ALOS (14.6%). These findings reaffirm the potential of UAV technology for precision hydraulic modeling and emphasize the trade-offs between high-resolution data and computational requirements. The study highlights the complementary roles of UAV and satellite data. In brief, UAV Data is Ideal for localized studies requiring high precision. Limitations include operational constraints, higher costs, and limited coverage. However, Satellite Data is Suitable for large-scale applications, offering cost-effective and widely available solutions despite lower spatial resolution. These insights guide decision-making in selecting appropriate data sources for specific hydrological applications.

Conclusion: This study underscores the efficacy of UAV-derived DEMs in enhancing hydraulic simulation accuracy, particularly for flood management and risk assessment. While UAVs excel in precision, ALOS satellite data provides a cost-effective alternative for broader applications. Key findings include: UAV-derived DEMs deliver superior performance in predicting hydraulic parameters, offering lower maximum depths and reduced error margins compared to ALOS data. ALOS DEMs, despite lower resolution, are sufficiently accurate for peak discharge predictions, making them viable for cost-sensitive projects. The implementation of rainfall as a

boundary condition demonstrates the potential to simplify hydraulic modeling by eliminating the need for separate hydrological studies. Higher temporal and spatial resolution in UAV simulations enables more accurate representation of flood dynamics, particularly at peak flows. Integrating UAV and satellite data offers a balanced approach to achieving accuracy and scalability in hydraulic modeling. The research paves the way for future advancements in hydraulic modeling, emphasizing the need for innovative data acquisition methods and enhanced computational techniques. Recommendations include deploying advanced UAV sensors, utilizing multiple UAVs for larger coverage, and leveraging machine learning algorithms to streamline data processing and improve predictive accuracy. By addressing the limitations of both UAV and satellite data, the study provides a roadmap for optimizing hydraulic simulations, contributing to more effective flood risk management and decision-making.

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ترکیب فناوری‌های ماهواره‌ای و پهپادی برای شبیه‌سازی‌های هیدرولیکی با وضوح‌بالا: مطالعه موردی در حوزه آبخیز مارون ایران

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چکیده

این مطالعه بر ارزیابی و مقایسه اثربخشی مدل‌های رقومی ارتفاع (DEM) با وضوح بالا که از داده‌های پهپاد (UAV) و ماهواره‌ای (ALOS) به‌دست آمده‌اند، برای شبیه‌سازی‌های هیدرولیکی تمرکز دارد. این پژوهش که در حوزه آبخیز مارون در ایران انجام شده است، دقت این مدل‌های رقومی- ارتفاعی را در مدل‌سازی رویدادهای سیل با استفاده از شبیه‌سازی دوبعدی به‌وسیله مدل عددی HEC-RAS (نرم‌افزار شبیه‌سازی هیدرولیکی) مورد بررسی قرار می‌دهد. با یکپارچه‌سازی داده‌های بارش و اندازه‌گیری‌های جریان سیلاب، این مطالعه بر پتانسیل داده‌های حاصل از پهپاد برای مدل‌سازی دقیق هیدرولیکی تأکید دارد، درحالی‌که قابلیت کاربرد داده‌های ماهواره‌ای رایگان را برای استفاده‌های گسترده‌تر نیز مورد بررسی قرار می‌دهد. این مقایسه دوگانه، دیدگاه‌های ارزشمندی برای مدیریت سیلاب فراهم می‌کند، به‌ویژه در مناطقی که دستیابی دقیق به داده‌ها و واکنش به‌موقع اهمیت زیادی دارد.

سابقه و هدف: سیل‌ها یکی از مهم‌ترین بلایای طبیعی در سراسر جهان هستند که خسارات اقتصادی و انسانی قابل‌توجهی به همراه دارند. تغییرات اقلیمی این مخاطرات را تشدید می‌کند. با شبیه‌سازی رفتار جریان، شناسایی مناطق مستعد سیلاب و کمک به توسعه راهکارهای کاهش اثرات، موجب افزایش کارایی مدیریت سیلاب می‌شود. بدین‌منظور، مدل‌های رقومی ارتفاعی داده‌های پایه‌ای مربوط به توپوگرافی و ناهمواری زمین را برای این شبیه‌سازی‌ها فراهم می‌کنند. این مطالعه به بررسی قابلیت‌های مدل‌های رقومی ارتفاعی حاصل از پهپاد که به‌دلیل دقت مکانی بالا شناخته شده‌اند، و مدل‌های رقومی ارتفاعی ماهواره آلوس (ALOS)، که پوشش گسترده‌ای در سطح پایین‌تری از دقت دارند، می‌پردازد. پهپادها با فراهم‌آوردن داده‌های دقیق، به‌ویژه در مناطق محلی و کوچک، تحول مهمی در مدل‌سازی سیلاب ایجاد کرده‌اند. در مقابل، داده‌های آلوس به دلیل دسترس‌پذیری گسترده و هزینه کم‌تر، برای کاربردهای در مقیاس وسیع

مناسب‌تر هستند. با به‌کارگیری هر دو منبع در مدل‌سازی هیدرولیکی دوبعدی، این مطالعه ارزیابی جامعی از نقاط قوت، محدودیت‌ها و امکان یکپارچه‌سازی آن‌ها را ارائه می‌دهد.

مواد و روش‌ها: این پژوهش در منطقه پسکوهک شیراز، ایران، انجام شد که ناحیه‌ای به مساحت ۳/٤ کیلومترمربع از حوزه آبخیز مارون را در بر می‌گیرد. داده‌های بارندگی و جریان رودخانه از طریق ایستگاه‌های محلی جمع‌آوری شد، درحالی‌که مدل‌های رقومی ارتفاعی از پهپاد و ماهواره آلوس استخراج شدند. برای تصویربرداری با وضوح‌بالا، از پهپاد استفاده شد و پردازش داده‌ها منجر به تولید مدل‌های رقومی ارتفاعی با دقت مکانی ۵ سانتی‌متر و دقت عمودی ۲ سانتی‌متر شد. داده‌های ماهواره آلوس با دقت مکانی ۵/۱۲ متر به کمک داده‌های پهپاد کالیبره شد تا قابلیت مقایسه و اطمینان‌پذیری افزایش یابد. برای شبیه‌سازی‌های هیدرولیکی، از نرم‌افزار HEC-RAS 2D استفاده شد. در این مطالعه، بارش به‌عنوان شرط مرزی در نظر گرفته شد که رویکردی نوین در مقایسه با روش‌های متداول مبتنی بر دبی است. کالیبراسیون و اعتبارسنجی مدل بر اساس هیدروگراف‌های مشاهده‌ای انجام گرفت و ضریب زبری مانینگ برای دستیابی به‌دقت بالاتر بهینه شد. برای حفظ تعادل بین دقت نتایج و کارایی محاسباتی، اندازه شبکه مدل‌سازی بادقت انتخاب شد. برای مدل رقومی ارتفاعی پهپاد، از شبکه ۲ × ۲ متر و برای مدل آلوس، از شبکه ۵ × ۵ متر استفاده شد.

یافته‌ها: مدل‌های رقومی ارتفاعی استخراج‌شده از پهپاد عملکرد بهتری نسبت به مدل‌های آلوس در نمایش ویژگی‌های زمین داشتند. وضوح مکانی بالاتر آن‌ها تصویری دقیق‌تر و واقعی‌تر از پیچ‌وخم کانال، تغییرات شیب و خصوصیات دشت سیلابی ارائه داد. این دقت منجر به شبیه‌سازی‌های هیدرولیکی دقیق‌تر، به‌ویژه در پیش‌بینی دبی اوج و زمان رسیدن به اوج شد. در مورد دبی اوج، مدل رقومی ارتفاعی پهپاد دبی اوج را با اختلاف ۸۵/۰ درصد نسبت به داده‌های مشاهده‌شده برآورد کرد، درحالی‌که مدل آلوس آن را ۲/۵ درصد بیش‌تر برآورد کرد. پیش‌بینی‌های مدل پهپاد تقریباً منطبق بر داده‌های مشاهده شده بود، درحالی‌که مدل آلوس زمان رسیدن به اوج را ٦/٨ درصد کم‌تر از مقدار واقعی برآورد کرد. مدل رقومی ارتفاعی پهپاد به‌طور مداوم عمق‌های حداکثری سیلاب کم‌تری را نسبت به مدل آلوس شبیه‌سازی کرد و با مشاهدات واقعی همخوانی بیش‌تری داشت. به‌عنوان نمونه، مدل پهپاد به‌طور میانگین عمق‌هایی ۲/۱٤ درصد کم‌تر از مدل آلوس پیش‌بینی کرد. این تفاوت‌ها برتری داده‌های پهپادی را در ثبت جزئیات دقیق‌تر عوارض زمین، که برای تخمین دقیق عمق سیلاب ضروری است، برجسته می‌کند. گنجاندن بارش به‌عنوان شرط مرزی پویایی و دقت شبیه‌سازی‌ها را افزایش داد. این روش در مقایسه با رویکردهای سنتی مبتنی بر سری‌های زمانی دبی، نشان داد که می‌توان نیاز به مطالعات جداگانه هیدرولوژیکی را برطرف کرد. شبیه‌سازی‌های مبتنی بر بارش، درک جامع‌تری از واکنش حوزه ارائه داد و به بهبود قابلیت‌های پیش‌بینی کمک کرد. هر دو مدل رقومی ارتفاعی پهپاد و آلوس هیدروگراف‌هایی تولید کردند که شباهت زیادی به داده‌های مشاهده‌ای داشتند، با این تفاوت که در شدت و زمان اوج تفاوت‌هایی مشاهده شد. مدل پهپاد، به دلیل وضوح زمانی بالاتر (فواصل ٦ دقیقه‌ای)، تغییرات سریع جریان را بهتر از داده‌های ایستگاه‌های هیدرومتری که در بازه‌های ساعتی ثبت شده بودند، شبیه‌سازی کرد. این قابلیت برای پیش‌بینی آنی سیلاب و

واکنش اضطراری بسیار ارزشمند است. شاخص‌های خطا، دقت برتر داده‌های استخراج‌شده از پهپاد را تأیید کردند؛ به‌طوری‌که خطای جذر میانگین مربعات برای مدل پهپاد ۰۲۲/۰ و برای مدل آلوس ۰۲٤/۰ به‌دست آمد و خطای نسبی در دبی اوج برای مدل پهپاد ۹/۱۰ درصد و برای مدل آلوس برابر با ٦/١٤ درصد بود. این یافته‌ها بر پتانسیل فناوری پهپاد برای مدل‌سازی هیدرولیکی دقیق تأکید دارند و نشان‌دهنده موازنه‌ای میان داده‌های با وضوح‌بالا و نیازهای محاسباتی هستند. این مطالعه بر نقش مکمل داده‌های پهپاد و ماهواره تأکید دارد. به‌طور خلاصه، داده‌های پهپاد برای مطالعات محلی که نیاز به‌دقت بالا دارند، ایده‌آل است؛ اما محدودیت‌هایی از جمله موانع عملیاتی، هزینه‌های بالاتر و پوشش محدود دارد. در مقابل، داده‌های ماهواره‌ای برای کاربردهای مقیاس بزرگ مناسب هستند و علی‌رغم وضوح مکانی کم‌تر، راه‌حلی مقرون‌به‌صرفه و در دسترس ارائه می‌دهند. این نتایج راهنمایی برای تصمیم‌گیری در انتخاب منابع داده‌ای مناسب برای کاربردهای خاص هیدرولوژیکی فراهم می‌کند.

نتیجه‌گیری: این مطالعه بر کارایی مدل‌های رقومی ارتفاعی استخراج‌شده از پهپاد در بهبود دقت شبیه‌سازی‌های هیدرولیکی، به‌ویژه در مدیریت سیلاب و ارزیابی ریسک تأکید دارد. درحالی‌که پهپادها در دقت برتری دارند، داده‌های ماهواره‌ای آلوس جایگزینی مقرون‌به‌صرفه برای کاربردهای گسترده‌تر ارائه می‌دهند. یافته‌های کلیدی شامل موارد زیر است: مدل‌های رقومی ارتفاعی پهپاد عملکرد برتری در پیش‌بینی پارامترهای هیدرولیکی ارائه داده و عمق‌های حداکثری کم‌تر و حاشیه خطای کاهش‌یافته‌ای را در مقایسه با داده‌های آلوس نشان می‌دهند. مدل‌های آلوس، علی‌رغم وضوح پایین‌تر، دقت کافی برای پیش‌بینی دبی اوج دارند و گزینه‌ای مناسب برای پروژه‌های کم‌هزینه محسوب می‌شوند. استفاده از بارش به‌عنوان شرط مرزی، پتانسیل ساده‌سازی مدل‌سازی هیدرولیکی را از طریق حذف نیاز به مطالعات جداگانه هیدرولوژیکی نشان می‌دهد. وضوح زمانی و مکانی بالاتر در شبیه‌سازی‌های پهپاد، امکان نمایش دقیق‌تری از پویایی سیلاب، به‌ویژه در جریان‌های اوج، را فراهم می‌کند. ادغام داده‌های پهپاد و ماهواره‌ای رویکردی متوازن برای دستیابی به‌دقت و مقیاس‌پذیری در مدل‌سازی هیدرولیکی ارائه می‌دهد. این پژوهش مسیر پیشرفت‌های آینده در مدل‌سازی هیدرولیکی را هموار می‌کند و بر ضرورت روش‌های نوین کسب داده و تکنیک‌های محاسباتی پیشرفته تأکید دارد. پیشنهادها شامل به‌کارگیری حسگرهای پهپادی پیشرفته، استفاده از چندین پهپاد برای پوشش وسیع‌تر و بهره‌گیری از الگوریتم‌های یادگیری ماشین برای تسهیل پردازش داده و بهبود دقت پیش‌بینی است. با پرداختن به محدودیت‌های داده‌های پهپاد و ماهواره، این مطالعه مسیر بهینه‌سازی شبیه‌سازی‌های هیدرولیکی را ترسیم کرده و به مدیریت مؤثرتر ریسک سیلاب و تصمیم‌گیری‌های بهتر کمک می‌کند.

استناد: ذوالقدر، مسیح، فتحی، اباذر، روستاپور، فاطمه، کارگر، محمدرضا (۱۴۰۴). ترکیب فناوری‌های ماهواره‌ای و پهپادی برای شبیه‌سازی‌های هیدرولیکی با وضوح‌بالا: مطالعه موردی در حوزه آبخیز مارون ایران. *پژوهش‌های حفاظت آب و خاک*، ۳۲ (۱)، ۱۵۱-۱۲۹.

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Introduction

Global warming contributes to bringing more water to the atmosphere, thus intensifying the precipitation and bringing up the link between floods and the atmospheric processes (1). Empirical studies have shown that climate change is responsible for moving floods both temporally and spatially and increasing their intensity. In Europe, floods are responsible for 40% of all economic losses and human casualties related to natural hazards (2). Despite significant human-induced changes, streamflow series are more influenced by variations in watershed rainfall, as observed in the Karun River basin, where recent increases in precipitation have led to higher averages in streamflow sub-series (3). Therefore, flooding is one of the phenomena that can cause significant loss of life and property. One of the initial actions in flood management projects is the hydraulic analysis of flow in flood-prone rivers using models. Flood modeling in ungauged watersheds remains a significant challenge, necessitating the development of robust methods for promising results in estimating flood hydrographs with limited data (4).

To implement hydraulic models, spatial ground data or bathymetry is required. Various sources such as satellite data and Unmanned Aerial Vehicle (UAV drone) data are available to obtain these data. Therefore, the correct selection between the available sources is of particular importance and necessity, and it can affect flood management decision-making as well as the accuracy of simulation results. Accurate spatial data can significantly enhance the precision of hydraulic simulations, leading to better predictions of flood behavior and improved preparedness and response strategies. By carefully choosing between satellite and UAV data, researchers and practitioners can optimize the effectiveness of their flood management efforts, ensuring that both immediate and long-term measures are based on the most reliable information available. The importance of selecting the appropriate data source cannot be overstated, as it directly influences the quality and reliability of the hydraulic models used in flood risk assessment and mitigation. In this study, DEM data from UAV and open-access satellite data were used as input to 2D hydraulic simulations for flood inundation.

The use of drones in flood mapping (UAVs) has become a widely adopted technique due to their potential to deliver high-resolution, real-time information that is crucial for the implementation of effective flood management and mitigation strategies that are effective. Open-access Digital Elevation Model (DEM) products are another widely used method for obtaining surface feature information (5). What follows is a summary of the studies that have been carried out on the two methods of flood modeling discussed herein.

(6) utilized LiDAR technology mounted on UAVs for flood modeling at a high resolution in a small mountain basin and a large urban region as well. They verified the flood modeling methods by traditional means and showed that UAV-LiDAR-derived data contains detailed elements such as small channels and streams that are crucial for flood behavior. Therefore, this technology, in essence, greatly enhances the resolution and accuracy of flood model simulations to a great extent. (7) posed UAV-borne LiDAR as a solution to their problem by using it to create very high-resolution digital elevation models for three different locations in Accra, Ghana. The study examined how much introducing such detailed topographic data into flood modeling would alter the results and the conclusion is that the Digital Terrain Models (DTM) with 0.3 m resolution from UAVs, provided more accurate results than the ones that used non-ground references, which were 10 m DTM. As a result, overestimating water flows in flat regions was reduced by as much as 62.5% when compared to the course DTM.

(8) carried out a study on the ability of UAVs to produce Digital Elevation Models (DEMs) to improve flood hazard mapping in small basins. They used different DEMs

as input to a 2D hydraulic model (FLO-2D) and compared the performance of UAV-derived DEMs with freely accessible and traditional DEMs. The authors stated that UAVs produced DEMs that were more accurate than the conventional method in flood simulation forecasting. They particularly highlighted its reliability in predicting flood extents and depth. (9) used DEMs created from UAV (Unmanned Aerial Vehicle) imaging with LiDAR-aided ground control points (LCPs) for flood applications. They used both UAV-derived DEMs and a LiDAR-based reference to compare flood estimation results. The authors demonstrated that georeferencing with LCPs resulted in DEM files with acceptable vertical uncertainty levels, and UAV-derived DEMs were found to be a complementary tool to LiDAR for local-level flood studies. The other approach to grasp the underlying surface is open-access satellite (10), data and ALOS satellite data have been widely recognized and utilized in hydraulic and hydrologic simulations across various studies. For example, (11) and (12) have indeed been looking into advanced technologies with the integration of ALOS data to get a more accurate flood modeling result. Similarly, (13) are also involved in the process of improving these methods, showing they have been consistently getting better results in the use of ALOS data for hydrology applications.

(14) assessed different DEM files obtained from various sources such as Copernicus Global Land Operations (GLO), Advanced Land Observation Satellite (ALOS), Cartosat, Shuttle Radar Topography Mission (SRTM), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) for hydrology purposes including watershed delimitation, hydraulic simulation, and statistical analysis in the Mahi River basin in India. The research found that ALOS and GLO are the most trustworthy methods for obtaining high-resolution topography data needed for detailed analysis and modeling. (15) utilized open-access DEMs namely SRTM, MERIT, Coastal DEM, GDEM, NASADEM, and AW3D30 for flood inundation mapping in a small flat river basin in China. They discovered that if a single DEM's output is sourced from different providers, it can cause a skew of the flood mapping results. The research highlights the necessity of providing correct and high-resolution DEMs, which will guarantee the minimization of the uncertainties in flood mapping. (16) employed ALOS, SRTM, and ASTER DEMs to test how reliable DEM outputs are for hydraulic modeling and flood mapping. They acknowledged that the findings aligned with ALOS-30 m model and ground-based DEM, with MAPE, reported the complicated land surface of river basin between 2.76 m and 5.58 m. Their research emphasizes the importance of high-quality DEM in flood risk evaluation and shows the capability of ALOS DEMs to improve flood modeling in areas lacking data. (17) studied DEM resolutions from 1 to 50 meters for flood modeling. They used HEC RAS 2D simulations, across all scenarios. The researchers noted that the selection of DEM resolution affects how river channels and their hydraulic characteristics are depicted, influencing flood simulations. Moreover, finer DEM resolutions offer representation of elements and terrain but could lead to higher computational expenses and data needs.

(18) evaluated how well HEC RAS 2D performs in assessing storm related hazards using the rain, on grid (RoG) modeling method as a standard in areas without gauges. They compared the results of HEC RAS 2D with those from a well-known model. The researchers concluded that with parameter tuning, validation and the rain on grid technique, HEC RAS 2D is effective for evaluating storm related hazards in regions. In a study, by (19) they utilized the log Pearson type III distribution to estimate floods for varying return periods. This information was then entered into HEC RAS to analyze flood levels, which were further integrated with ArcGIS to generate floodplain maps. The researchers endorsed the application of HEC RAS, for simulating water levels under flood recurrence intervals. (20) examined flood risk in the Khazir River in Iraq by combining

HEC-RAS with the HEC-GeoRAS extension in ArcGIS. The authors assessed numerous rainstorm events with varying flows and flood return times. They stated that employing HEC-RAS demonstrated robust correlations for varying flood depths and speeds, proving the model's suitability for assessing flood risks. (21) examined the efficacy of multiple satellite-based digital elevation models (DEMs) and a UAV-based digital terrain model (DTM) for flood modeling in a two-dimensional (2D) hydraulic model. In comparison to satellite-based DEMs, the results demonstrated that the 2D flood model utilizing the UAV-based DTM offered superior estimations of flood characteristics like arrival time, depth, duration, and extent. It was discovered that the UAV technique was highly helpful for producing precise topography data in flood modeling when combined with field measurements and ground control points.

Hydraulic models play an essential role in determining flood-prone areas, and both one-dimensional (1D) and two-dimensional (2D) hydraulic models can be employed for accurate flood predictions. Most used models assume the flow to be one-dimensional and simulate the hydraulic parameters of the flow based on the one-dimensional Saint-Venant equations. The assumption of one-dimensional flow is justifiable in most river reaches, but in certain sections of the river, the flow mechanism follows two-dimensional (22). In a comparative study, (23) evaluated the performance of four 1D and 2D hydraulic models-HEC-RAS 1D, HEC-RAS 2D, LISFLOOD-FP Diffusive, and LISFLOOD-FP Sub-grid—concerning their sensitivity to surface roughness characteristics. The comparison was conducted across four different rivers using identical input data and boundary conditions. The study found that the performance of the 1D model was comparable to that of the 2D models. The performance of the 2D models improved with increasing channel roughness, while the 1D model's performance was positively affected by increasing floodplain roughness. When the models were evaluated based on their ability to describe uniform roughness versus distributed roughness in the floodplain, uniform surface characteristics provided better results compared to distributed roughness characteristics.

Software tools like HEC-RAS provide predictions of water levels along rivers and can be used to simulate flood extents. (24) applied the HEC-RAS software for flood modeling and utilized UAV data to update boundary conditions of hydraulic models. The authors employed boundary conditions derived from UAV-produced DTM/DSM observations, with initial conditions and additional data obtained through calibration. To periodically update the model (weekly, monthly, annually), new boundary condition data were incorporated. The focus of the study was on the accuracy of new observations and methods to improve data processing. The findings demonstrated that data updates aimed at providing more precise information can lead to enhanced predictions of flood-prone areas, ultimately improving the reliability of flood warning systems.

(25) and (26) provide historical perspectives on the evolution and early successes of ALOS data in such simulations, showcasing its enduring relevance. Conversely, recent research has increasingly focused on UAV-derived bathymetric data for simulating flood hydraulics. Studies by (27), (28), (29), and (30) explore innovative methodologies and applications of UAV technology, highlighting its growing role in enhancing spatial resolution and data timeliness compared to traditional methods. These comparative advancements underscore the complementary benefits of integrating ALOS satellite and UAV-derived data to bolster the accuracy and reliability of hydraulic simulations in diverse environmental contexts.

In this study, ALOS and UAV data were used as input to HEC-RAS 2D simulation for flood mapping. The literature survey indicated that researchers usually have applied one of these techniques (UAV or ALOS) to obtain DEM files as input to hydraulic model, and even if they utilized both approaches, 1D HEC-RAS simulations were performed. Thus, to the best of authors' knowledge, there is no study comparing the results of these two techniques applying HEC-RAS 2D simulation. 2D simulation is suggested by (31) for future studies which is performed in the current research. Moreover, the implementation of precipitation as a boundary condition is a newly added feature in HEC-RAS, which is considered in this study. Typically, discharge time series are usually introduced as boundary conditions as a common practice in similar studies. This study conducts hydraulic simulations utilizing both satellite and UAV data, validating their outcomes against observed data. It explores whether engineers can exclusively depend on freely available satellite data or if UAV flights are indispensable for precise data acquisition within specific locales. Traditionally, river simulations have predominantly utilized terrestrial mapping or satellite imagery. This research breaks new ground by integrating satellite and UAV data into hydraulic simulations with new and enhanced boundary condition implemented in the numerical model, systematically comparing their results with observed data to ascertain the feasibility of relying solely on satellite data. Additionally, it evaluates the accuracy of each method relative to real-world measurements, marking a significant advancement in hydraulic modeling methodologies. Moreover, the study examines the incorporation of a new feature in HEC-RAS software that considers rainfall inputs, contrasting with previous approaches that typically applied discharge as boundary conditions.

Materials and Methods

Study area: to determine rainfall intensity values for the Maroun watershed, a 4.3 square kilometer area within the Paskuhak region of Shiraz, Capital of Fars province in Iran (UTM Zone 39R), data from the local rainfall gauge managed by Shiraz's water organization were utilized. The precipitation and flood data were obtained from Shiraz's water organization. The precipitation data were obtained using a rain gauge that records and measures rainfall consistency which was a Lambrecht model with 0.1 mm accuracy. The flood data was recorded at the location by the instrumentation installed by the water organization of Fars province, located downstream of the study area. The hydrometric station records the flood discharge in one-hour intervals. The watershed features shallow soil with a medium to loamy texture, low permeability, and moderate vegetation cover predominantly composed of Pistacia atlantica (mountain pistachio) yielding a curve number of 78 which was considered in the simulations. Depth profiling data was defined using both UAV and ALOS satellite imagery, as depicted in Figure 1, with point A marking the confluence of the river in both digital elevation models (DEMs). This integration of UAV and satellite data is crucial for accurately characterizing the topography and hydrological conditions of the Maroun watershed, essential for effective rainfall intensity assessment and hydrological modeling efforts in the area.

The drone used in this research was the Phantom 4 Pro model. During the aerial imaging, the geographical position and the static status of each image were recorded by the internal GPS and IMU (Inertial Measurement Unit) of the drone and appended to the images. After transferring the images to a computer, various processing steps were carried out using Agisoft PhotoScan software to create a Digital Surface Model (DSM) and an Ortho mosaic. During the processing, the images were aligned using the geographical data attached to each image. After aligning the images, the matching process and the creation of tie points resulted in the generation of a sparse point cloud using the Structure from Motion (SFM) algorithm. SFM is a photogrammetric technique that reconstructs 3D structures from a series of overlapping 2D images. By analyzing feature points across images taken from different viewpoints, SFM estimates camera positions (motion) and 3D geometry (structure). The following steps were involved in the SFM process:

1- Image Alignment with GPS/IMU Data: Images were aligned using GPS and IMU data to provide initial positional information.
2- Feature Matching and Sparse Point Cloud (SFM): Feature points were matched across the aligned images, generating a sparse point cloud.
3- Georeferencing with Ground Control Points (GCPs): Ground control points were used to georeference the sparse point cloud, ensuring accurate geographic positioning.
4- Dense Point Cloud Generation (MVS): Multi-View Stereo (MVS) algorithms were applied to generate a dense point cloud from the sparse point cloud.
5- DEM/DSM and Ortho Mosaic Creation: Digital Elevation Models (DEM) and Digital Surface Models (DSM) were created from the dense point cloud, along with orthorectified mosaics for detailed visualization.

To increase the accuracy of the final extracted model, the sparse point cloud was georeferenced using multi-frequency satellite receiver ground stations. Upon completing this process, a dense point cloud and then a Digital Elevation Model (DEM) with an RMSE error of 2 cm in the vertical and horizontal directions and a spatial resolution of 5 cm were produced.

After obtaining the Digital Elevation Model from the ALOS satellite data with a spatial resolution of 12.5 meters, its accuracy was assessed using the drone's Digital Elevation Model to ensure reliable results. The study utilizes two datasets: a reference Drone DEM and a test ALOS DEM. The Drone DEM, with its high accuracy (2 cm RMSE and 5 cm resolution), serves as the reference dataset. On the other hand, the ALOS DEM is a satellite-derived product with a resolution of 12.5 m, chosen as the test dataset for evaluation. Both DEMs are georeferenced to the same coordinate system (e.g., WGS84 UTM) to ensure accurate spatial overlap. For validation purposes, independent Ground Control Points (GCPs) surveyed using high-precision GNSS (e.g., from multi-frequency ground stations) are employed. These GCPs are used to validate the accuracy of the drone DEM (already done during processing). The process of creating DEM using UAV is depicted in figure 2.

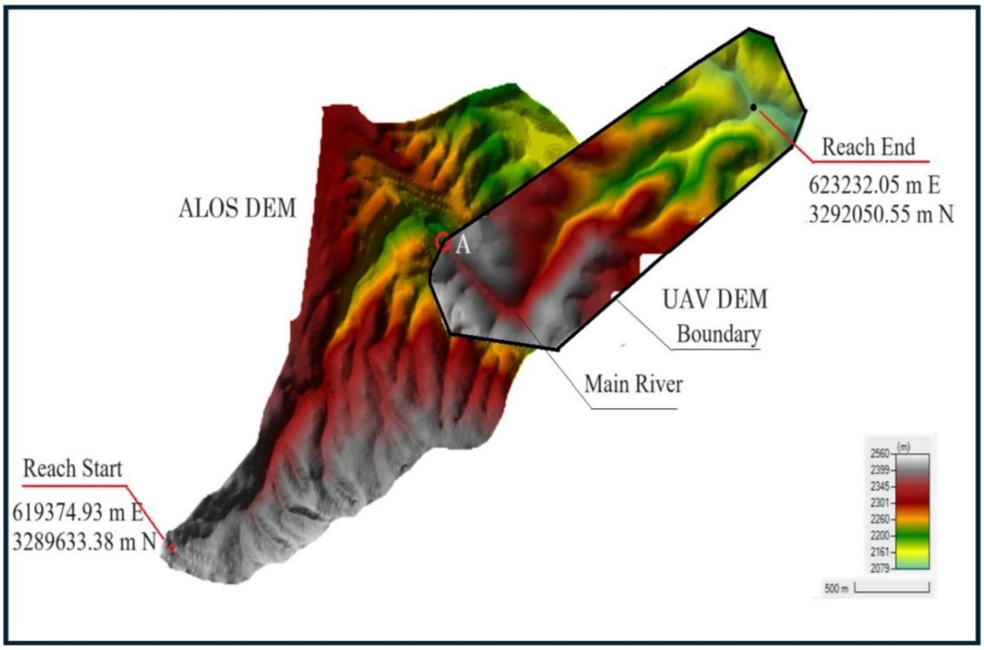

Figure 1. Position of the digital elevation models (DEMs) from the two sources relative to each other.

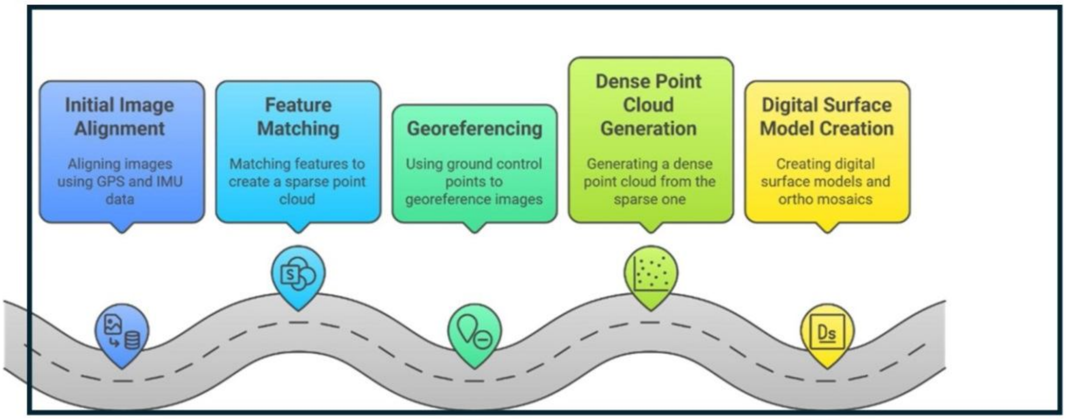

Figure 2. UAV image processing workflow.

Numerical model: For conducting 2D hydraulic simulation, version 6 of the HEC-RAS software was employed. Developed by the US Army Corps of Engineers, Hydrologic Engineering Center, this model solves continuity and momentum equations in the X and Y directions, accounting for incompressible flow. The model solves the 2D Shallow Water Equation using the Finite Volume algorithm with an implicit method. The algorithm can handle subcritical, supercritical, and mixed flow regime. Compared to traditional methods like finite difference and finite elements, it provides greater soundness and stability. This allows for modeling of dry areas and sudden flow rushes over the underlying terrain.

Regarding the mesh, HEC-RAS offers both structured and unstructured meshes, with each cell being orthogonal to the others. This feature enables the creation of triangle, square, rectangle and five- to six-sided cells, resulting in high-speed computation and accurate representation of the underlying terrain.

Model calibration: The numerical simulation of the digital elevation models (DEMs) derived from ALOS satellite and UAV data using the regional water authority's data was conducted in HEC-RAS software. The 2D simulation of the DEMs was discretized within the software environment, and multiple simulation runs were executed to determine the optimal mesh for each DEM model. The simulation results can assist us in accurately determining the appropriate mesh size. In this study, to reach an acceptable degree of mesh sizes, simulations with different mesh sized ranging from 20m to 1.5 m were performed for UAV and ALOS DEMs. It was found that after a certain value, reducing mesh sizes did not have significant influences on the accuracy of results. Thus, a mesh size of 2 meters by 2 meters was selected for the UAV-derived DEM, and 5 meters by 5 meters for the ALOS-derived DEM, based on their suitability for the Maroun watershed. In this study, Precipitation was introduced as boundary condition, which is a feature recently added to HEC-RAS. Additionally, the normal depth was considered as downstream boundary condition as well.

For the ALOS-derived DEM, downstream boundary conditions considered normal depth, while rainfall was applied as a boundary condition across the entire watershed. Due to the smaller coverage area of the UAV-derived DEM compared to the entire Maroun watershed, uniform rainfall input could not be applied to both DEMs. To address this issue, after simulating the ALOS-derived DEM at point A (Figure 1), where it diverges from the UAV-derived DEM, the flow hydrograph was extracted and used as a boundary condition for the UAV-derived DEM. Among the parameters requiring calibration in the mathematical models is the bed roughness coefficient. Typically, the roughness coefficient varies across different cross-sectional areas to achieve acceptable conformity with measured flow parameters such as depth or discharge. In this study, calibration of the HEC-RAS model was feasible due to the presence of a hydrometric station on the Maroun River.

The Manning's roughness coefficient (n) was obtained using the Cowan method as follows:

$$n=(n0 + n1 + n2 + n3 + n4)\ m5 \qquad (1)$$

The base roughness coefficient n0 to n4 is not chosen based on the channel material. The coefficients n0 to n4, respectively, represent the irregularities of the channel cross-section, the presence of obstacles in the channel path, vegetation cover, and the degree of meandering of the channel path. After conducting a field survey and regarding the value suggested by Cowan the values of n0 to n5 were substituted and the value of 0.039 was obtained as the manning roughness coefficient:

$$(0.009 + 0.002 +0.003 + 0.020)1.15 = 0.039 \qquad (2)$$

The above number was introduced as the initial value for validating the numerical model in the software. The flood hydrograph of February 16, 2017, was also chosen for calibration, and the Manning calibration model was performed as a result, resulting in a calibrated Manning coefficient of 0.055. Figure 3 shows the results of validating the numerical model. All hydrographs represent simulated versus observed discharge at the downstream hydrometric station of the study reach.

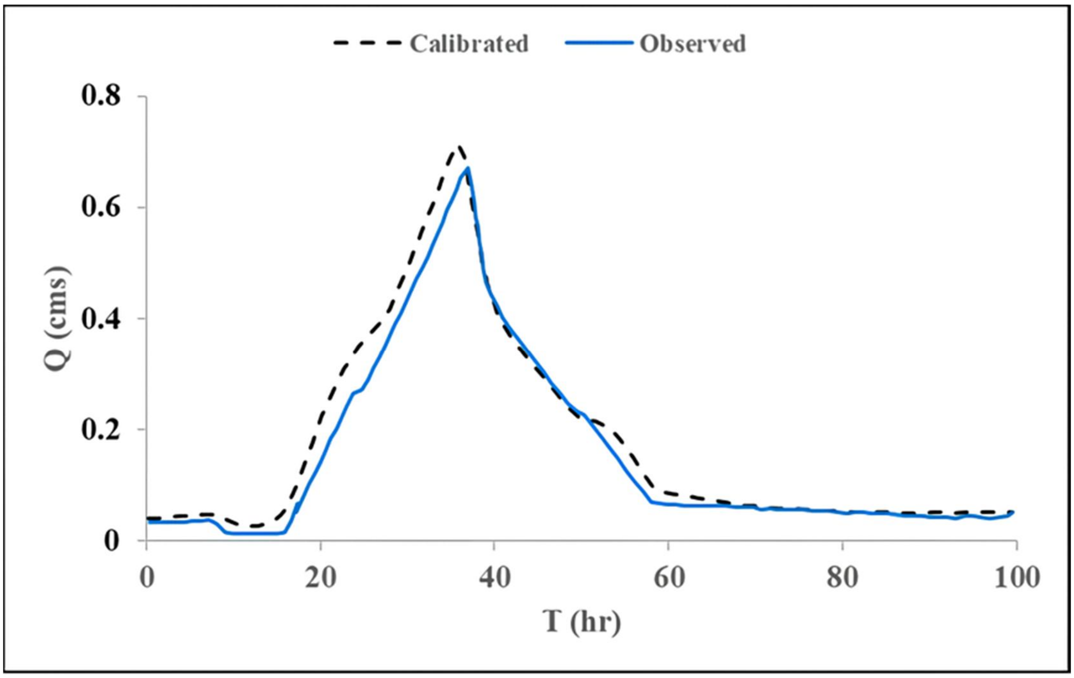

Figure 3. Calibration Hydrograph of Manning Coefficient based on February 16, 2017, event.

In addition, error metrics were applied to compare the outputs of ALOS and UAV with observed data that are shown in Table 1.

Table 1. Statistical indicators used in the research.

Statistical index	Equation
Mean squared error	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}$
Normalized root mean square error	$NRMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n} x_i{}^2}}$
Relative mean error index	$MRE = \frac{1}{n}\sum_{i=1}^{n} RE_i$
Relative error in peak discharge calculation	$RE_{Qp} = \left\lvert\frac{Q_o - Q_p}{Q_p}\right\rvert \times 100$
Relative error in time to peak calculation	$RE_{TP} = \left\lvert\frac{T_o - T_p}{T_p}\right\rvert \times 100$

Results and Discussion

Validation of the numerical model: After calibrating the numerical model, flood simulation using both digital elevation models (DEMs) derived from ALOS satellite and UAV sources, the results were compared with recorded flood data (Figure 4).

As observed, the overall shape of the hydrographs has been simulated with acceptable accuracy. The presence of a stream gauge station at the watershed outlet and rainfall measurements within the watershed significantly contributed to the desirable reconstruction of the hydrograph shape. This consistency in both the rising and falling limbs of the hydrograph compared to its peak is noteworthy. In other words, the simulation accuracy, using both bathymetry sources, is higher at lower flow rates compared to the peak flow intensity of the hydrograph. These results underscore the importance of comprehensive data collection within the watershed, which enhances the accuracy of hydraulic simulations. The accurate representation of the hydrograph shape, particularly at lower flow rates, suggests that the models are well-calibrated and capable of capturing the essential dynamics of the watershed's response to rainfall. Consequently, the high fidelity of these simulations can significantly improve flood forecasting and water resource management in the region, demonstrating the practical utility of integrating precise hydrometric and rainfall data in hydraulic modeling efforts.

It is noteworthy that the peak flows predicted by the ALOS and UAV models are close to each other. One reason for this could be the boundary condition input introduced from the ALOS model to the UAV model. In other words, the UAV hydrograph model has accepted the ALOS hydrograph model as its upstream input and has simulated its course along the river. Therefore, the predicted maximum flow values of both models are close to each other. However, as observed, the time to reach peak flow in the UAV model is consistently later than in the ALOS model. The reason for this could be attributed to the difference in spatial resolution between the ALOS-derived digital elevation model (DEM) and the UAV-derived DEM. The spatial resolution of the ALOS satellite data is 12.5 meters, whereas the UAV data has a spatial resolution in the range of millimeters to centimeters. In other words, the terrain or depth sounding in the ALOS model is interpolated at points spaced 12.5 meters apart, whereas in the UAV model, interpolation is done at points spaced only a few millimeters or centimeters apart. This higher resolution in UAV-based allows them to capture the underlying terrain’s details more accurately, including channels, meandering, ridges, micro-drainage networks, and obstacles. As a result, water and natural drainage are better represented, leading to increase runoff concentration in the main channel and larger time to peak. In contrast, satellite-based DEMs have courser resolutions, which fail to capture these finer features, and generally oversimplify the path, resulting in less runoff concentration and a shorter time to peak. Additionally, UAV DEMs ensure higher vertical accuracy compared the satellite DEMs. Uncertainty in elevation data alter flow velocities and cause artificial water retention, which contribute to shorter time to peak (15, 32 and 33).

Consequently, the flood travel time in the UAV model is expected to be longer than in the ALOS model and closer to reality. Figure 5 illustrates a common segment of the path estimated by both UAV and ALOS sources.

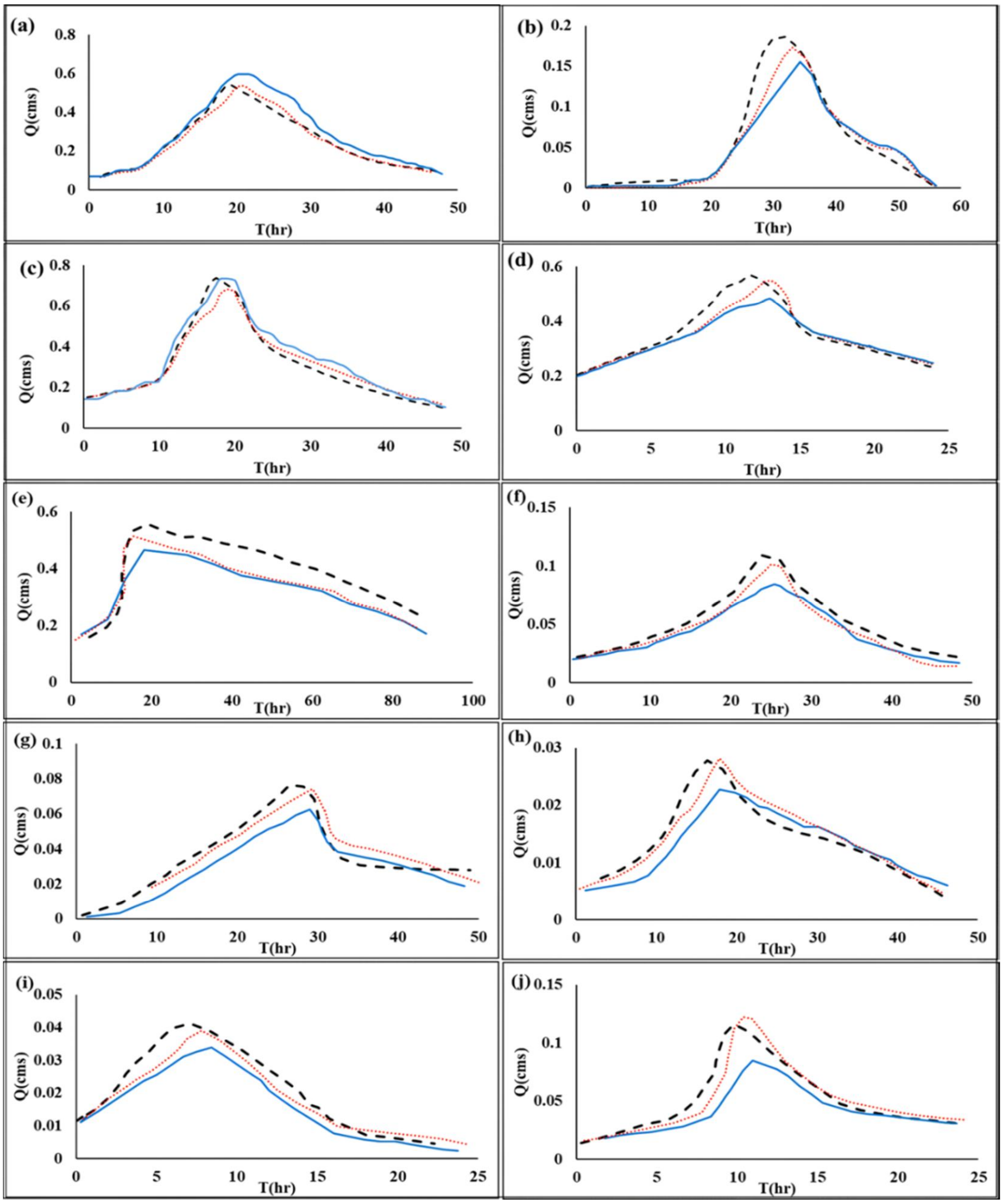

Figure 4. Comparison of Predicted hydrographs against ALOS and UAV generated bathymetries; a) 11 Dec. 2012 b) 1 Feb. 2017 c) 22 Dec. 2012 d) 2 Jan 2016 e) 12 Feb 2017 f)30 March 2017 g)22 Nov. 2017 h) 25 Feb 2018 i) 29 April 2018 j) 29 Jan. 2019. ALOS (– – –), UAV (⋯⋯⋯), Observed (———).

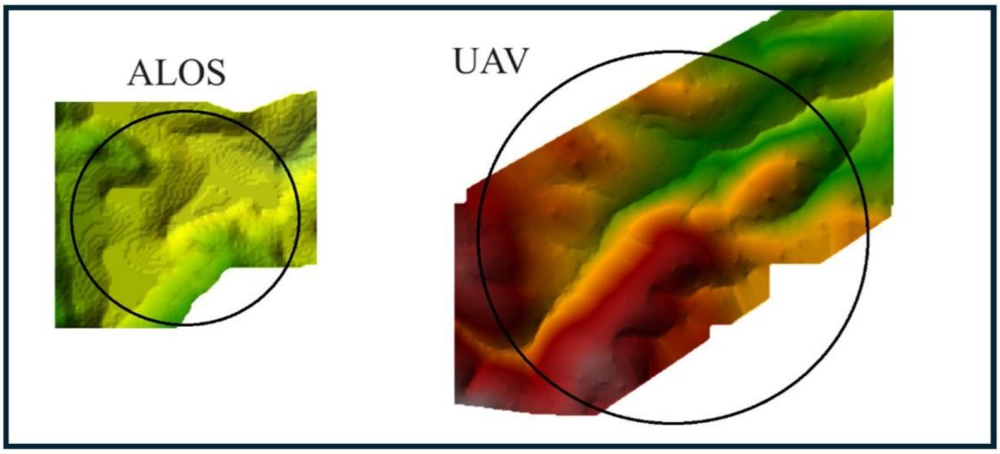

Figure 5. Common segment of bathymetry generated by ALOS and UAV.

By examining this figure, it is evident that the terrain topography in the UAV model is more accurate and closer to reality. The UAV model's higher spatial resolution allows for a more precise representation of the terrain's features, which significantly enhances the accuracy of hydraulic simulations. Regarding the peak points of the hydrographs, it is important to note that the flood data recorded at the stream gauge station was captured at hourly intervals. Consequently, in many instances, the peak point appears flattened because the actual peak of the flood occurred during the unrecorded time, and only the hours before and after were documented. This limitation contrasts with the simulated hydrographs in the numerical model, where the time intervals can be adjusted to provide a more detailed representation of the flood event. In the current study, outputs were recorded at 6-minute intervals, allowing for a finer resolution of the peak graph. This finer resolution enables the model to capture the rapid changes in flow rates that occur during the peak of the flood, which are often missed in observational data due to the coarser time intervals. The result is a more accurate and detailed hydrograph that better represents the dynamics of the flood event. The ability to adjust time intervals in numerical models is a significant advantage, as it allows researchers to capture and analyze the critical moments of a flood with greater precision. This enhanced accuracy is particularly important for flood risk management and mitigation, as it provides more reliable data for decision-making processes. The detailed hydrographs produced by the UAV model can help in understanding the flood behavior more comprehensively, leading to better-informed strategies for flood prevention and control. The comparison between the blocky observational hydrographs and the finely detailed simulated hydrographs highlights the importance of using high-resolution data and appropriate time intervals in hydraulic modeling. This approach ensures that the peak flow rates and other critical aspects of the flood event are accurately represented, ultimately contributing to more effective flood management practices. However, it is worth noting that ALOS data, despite being a free source, can still be useful for predicting peak discharge, though it tends to underestimate the time to peak.

In the study, maximum depths from both ALOS and UAV datasets were compared, revealing that the maximum depth from the UAV digital elevation model (DEM) is less than that from the ALOS DEM (Table 2). This indicates that the UAV DEM, with its finer spatial resolution, enhances simulation accuracy, resulting in a lower maximum depth simulated for the flood event. The finer resolution of the UAV DEM allows for more precise capture of terrain features, leading to more accurate hydraulic modeling. Throughout this research, all data consistently showed higher maximum depths in the ALOS DEM compared to the UAV DEM. This trend underscores the superior accuracy of UAV-derived data in representing topographic details and simulating flood depths. The improved accuracy of the UAV DEM can significantly enhance flood risk assessments and management practices by providing more reliable data for hydraulic simulations. Consequently, the use of UAV-derived DEMs in hydrological studies is recommended for achieving higher precision in flood modeling and other related applications.

Table 2. Maximum Water Depths in the Simulation Model of ALOS and UAV Digital Elevation Models.

Event	Max. water depth (m)		Percentage of difference
	ALOS	UAV	
A	2.96	2.49	17.25%
B	3.21	2.64	19.49%
C	2.15	1.87	13.93%
D	1.81	1.61	11.70%
E	0.93	0.82	12.57%
F	1.35	1.18	13.44%
G	1.07	1.03	3.81%
H	0.47	0.45	4.35%
I	0.86	0.77	11.04%
J	1.56	1.34	15.17%

Table 3 also displays various error metrics obtained from comparing outputs of the UAV and ALOS models with observational data. As observed, the UAV model demonstrates higher accuracy in simulating all hydraulic parameters.

Table 3. Average Error Metrics in Predicting Hydraulic Parameters by UAV and ALOS Models.

DEM	RMSE (QP)	NRMSE (QP)	MRE (QP) %	RE (QP) %	RE (TP) %
ALOS	0.024	20.580	2.420	14.600	9.167
UAV	0.022	12.162	2.210	10.916	1.630

In which RMSE and NRMSE are mean squared error and normalized mean squared error, respectively. REQP and RETP designate relative error in peak discharge and time to peak calculation and MRE stands for relative mean error index. n is the number of flood event data, xi and yi are observed and predicted peak discharge, respectively. QO is the observed discharge at the hydrometric station, To is the time to reach the peak flow of observation data, Qp is calculated peak flow and Tp is the time to reach the calculated peak flow.

The results of the current study were compared with findings from similar studies. (34) reported that reducing the spatial resolution of the digital elevation model (DEM) leads to a 10% increase in flow depth, which aligns with the findings of this research. Specifically, the average flow depth in the UAV model was found to be 10% less than that of the ALOS model. Additionally, (21) demonstrated that simulations of hydraulic parameters using UAV-derived DEMs exhibit higher accuracy compared to satellite-derived data. This corroborates the current study's results, which indicate that UAV data, with its finer spatial resolution and reduced error margins, provides more reliable inputs for hydraulic modeling and flood prediction. Such comparisons highlight the importance of selecting appropriate DEM sources for accurate hydraulic simulations, underscoring the significant advantages of using UAV-derived data in various hydrological applications.

Recent studies have explored the use of UAV derived DEMs for hydraulic modeling, comparing them to satellite and LiDAR-based DEMs. The results show that UAV DEMs provide consistent outcomes in flood simulations as well as affordable and accurate topographic data collection for small-scale flood hazard mapping (8). In tropical areas, UAV-DEMs provided comparable results to high-precision topography models, despite challenging field conditions (35). UAV-DEMs have also proven competitive with LiDAR-based DEMs for urban stormwater simulation, with flight altitude being the most influential factor affecting DEM quality (36). These comparisons highlight the consistency and validation of the current study's findings with prior research, emphasizing the advantages of using UAV-based digital elevation models for simulating hydraulic parameters due to their higher spatial resolution and enhanced accuracy. Additionally, these findings suggest that UAV-DEMs offer a promising alternative for hydraulic modeling, particularly in areas where high-resolution topography data is scarce or frequent updates are required.

Understanding the limitations, opportunities and challenges of both UAV and satellite data is crucial for scientists and engineers to manage their hydraulic and river engineering studies and enhance the reliability of their models. Both approaches have several limitations that can impact the accuracy and reliability of study findings. Spatial resolution is one of the most important differences, while UAVs provide high spatial resolution data, they can cover a limited area, making them suitable for small-scale studies. On the other hand, satellites can provide DEMs for large areas with lower spatial resolution (37). Both satellite and UAV data can be affected by weather and environmental conditions. Windy, rainy and extreme temperatures can either limit the application of UAVs or decrease their precision. Cloud cover can blur optical sensors of satellites and create gaps in data (38). Processing UAV data requires specialized software and expertise. However, satellite data can be easily accessed through available databases (39). Deploying UAVs in remote areas is logistically challenging. Additionally, obtaining probable permissions can be time-consuming, however satellite data is accessible in remote areas with lower resolutions (40). More details on limitations of challenges of UAV and satellite DEMs can be found at (41).

Although UAVs (Unmanned Aerial Vehicles) have demonstrated great potential in improving flood modeling, several studies have identified limitations associated with their use. (21) reported that in areas covered with trees, UAVs are unable to capture accurate terrain data, leading to vertical errors. This limitation necessitates additional ground surveys to obtain detailed and high-resolution data. Furthermore, (31) stated that UAV data acquisition can be time-consuming and costly, particularly when covering large areas. Additionally, factors such as rain, strong winds, or low visibility can hinder UAVs' ability to capture high-quality images and maintain stable flights. (42) tested UAV for topographic modeling through aerial photography in the Surena River in Norway. They found that for high spatial resolution, it is preferable to have sunny weather; however, if suitable weather conditions are not available, it is possible to edit the brightness and reflections on the water surface during processing.

Nevertheless, in some cases, even the most advanced processing methods cannot correct errors resulting from low-quality images caused by reflections, shadows, vegetation, or poor data quality.

Satellites can cover large areas, but often at a lower spatial resolution that affect the detail and accuracy of the topographic and bathymetric models used in hydraulic simulations. Cloudy weather can obstruct optical sensors leading to gaps in data or the need for image correction. Satellite data is more readily accessible but may require significant post-processing to be useful for specific applications (43).

Conclusion

This study underscores the effectiveness of UAV-derived data in improving hydraulic modeling accuracy for flood management, successfully replicating hydrograph shapes with contributions from stream hydrometric station data and comprehensive rainfall measurements within the watershed. This study further substantiates the advantages of UAV-based digital elevation models, which exhibit superior accuracy in flood simulations, while also recognizing cost-effectiveness and widespread availability of ALOS data for hydrological applications. The key findings of this study can be summarized as follows:

1- The UAV model demonstrated consistently superior performance in predicting hydraulic parameters, yielding lower maximum depths and reduced average flow velocities compared to the ALOS model. This improved performance can be attributed to the finer spatial resolution of the UAV model. Error metrics further highlighted the enhanced simulation capabilities of the UAV model.

2- The peak discharge estimated using the UAV DEM was 0.85% higher than the observed data, while the peak discharge estimated using the ALOS satellite DEM was 5.2% higher than the observed data.

3- The time to peak estimated using the UAV DEM was nearly identical to the observed data, whereas the time to peak estimated using the ALOS satellite DEM was 8.6% shorter than the observations.

4- The maximum depth estimated using the UAV DEM was 14.2% lower than that estimated using the ALOS satellite DEM, indicating the higher accuracy of the UAV data with a reduced error rate compared to the satellite data.

5- The implementation of rainfall as a new boundary condition in this study has proven to be effective, suggesting that separate hydrological studies may not be required when conducting hydraulic simulations.

6- ALOS satellite data, despite its coarser spatial resolution of12.5 meters, demonstrated acceptable accuracy in predicting peak discharge, making it a cost-effective alternative. However, the ALOS model consistently underestimated the time to peak flow, which can be attributed to its limited spatial detail.

It should be mentioned that although applying UAV and ALOS DEMs has many advantages, there are limitations associated with these approaches, like many others. For instance, limitations such as flight regulations, weather dependency, flight time, cost and data processing associated with UAV, while low resolution, calibration, cloud cover, post-processing and interpolation in large areas are restrictions that ALOS DEMs may face. As a suggestion, deploying more advanced sensors on UAVs and employing multiple UAVs for simultaneous data collection to improve the data quality can be considered. Machine learning algorithms can be used to preprocess UAV and satellite data to accelerate the analysis process and improve the results.

Alternative free satellite data for flood studies can be suggested for future studies. Sentinel-1 which provides synthetic aperture radar (SAR) imagery, highly effective for flood detection, even in cloudy conditions or at night, with resolution of 10 m can be an alternative source. Sentinel-2 which offers high-resolution multispectral imagery (10–20 m) is useful for mapping flood extent and monitoring vegetation/

water interactions. ALOS PALSAR, a radar-based dataset suitable for terrain modeling and flood inundation detection, especially in vegetated areas, can be considered for future suggestions. Additionally, alternative UAV options to improve flood mapping like Fixed-Wing UAVs Suitable for large-scale mapping with longer flight durations and efficient area coverage and Multi-Rotor UAVs ideal for detailed, localized flood assessments in areas with complex terrain and capable of carrying LiDAR sensors for high-accuracy elevation data can be considered for future studies as well.

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Data Source

The topographic data of this research was extracted from two sources: (free) satellite and drone. The recorded rainfall and flood data were also obtained from the Fars Regional Water Company. These data are available on request.

Conflict of Interest

There is no conflict of interest in this article, and this is confirmed by all authors.

Authors' Contributions

1. Masih Zolghadr: Research design and methodology, article revision and finalization, research supervision, article review.
2. Abazar Fathi: Drafting the article, participation in analyses, article review, visual presentation, field visits.
3. Fatemeh Rustapour: Data access and data collection, data preparation, performing calculations, modeling and simulation.
4. Mohammadreza Kargar: Data access and data collection, data preparation, performing calculations, preparing maps and spatial information, field visits.

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Ethical principles

All authors confirm that ethical standards were followed in the conduct and publication of this study.

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