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Forensic hydrological assessment of flood response under land use/land cover (LULC) change using ANN and HEC—HMS

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Machine learning and optimization applied to the assessment of flood hazard magnification by reservoir operation

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Abstract
The frequency of disastrous floods has significantly increased across the world in recent decades. Severe damage caused by floods in regions where river flow is regulated by reservoirs has caused the operation of reservoirs to be hotly debated. This paper presents a forensic optimal operation approach (FOOA) and a goal-attained approach (GAA) to investigate historical operation (HO) of reservoirs under floods to examine whether operational decisions contributed to increased flood damages. FOOA combines a reservoir inflow forecasting method with a simulation-optimization model to minimize the maximum release from the most downstream reservoir under floods using support vector machine (SVM) and the Genetic Algorithm (GA). GAA applies observed historical reservoir inflows to the simulation-optimization model for flood control. GAA and FOOA are developed in this study for the forensic investigation of Seimare and Karkheh reservoirs' operation during the 2019 floods, which was one of the three largest floods that have occurred in Karkheh basin, Iran, in the past 70 years. This paper's results show that historical reservoir operation intensified floods, as established by the finding that the average vulnerability of the reservoirs system to downstream damages under HO was 65 and 92% worse compared to FOOA's and GAA's. This study presents a methodology for improved decision-making to reduce future flood impacts, and advances the current understanding of how operational errors may magnify flood hazards.

Keywords Forensic engineering · Flood control · Reservoir operation · Standard operation policy · Optimization · Genetic Algorithm · Machine learning · Support vector machine

1 Introduction

Dams and reservoirs have been built for hundreds of years for securing water supplies, generating hydropower, mitigating floods, and serving other functions (Komisyonu 2000). Over the past 100 years, there has been a rapid increase in the number and storage capacity

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of reservoirs (Wang et al. 2024). The significant increase in the frequency and intensity of floods and the growth of population and property within flood plains have stimulated interest in reservoir construction worldwide (Zarei et al. 2023).

There is debate worldwide about the intensifying impact of reservoir operation on floods (Vahedifard et al. 2021; Zarei et al. 2023). For example, recent devastating floods of 2019 in different parts of the world raised questions as to whether reservoirs contributed to floods rather than abated them (Razavi et al. 2020). In Jan. and Feb. 2019, Queensland, Australia, experienced record-breaking precipitation, which caused major floods in the city of Townsville, downstream of the Ross River reservoir. The event inflicted five fatalities and more than $727 million in damage, and raised the concern that the mismanagement of the Ross River reservoir resulted in the extensive flooding and losses (Smee 2019). In March and April 2019, Iran was struck by three precipitation waves. The waves triggered severe floods in large parts of the country, where major rivers are regulated by reservoirs, left behind 76 fatalities and more than $2 billion in damage (Sarvestan et al. 2024). The public questioned whether reservoirs were operated properly in the flood areas (Zarei et al. 2021a). During the Spring 2019 the Mississippi river and its tributaries generated unprecedented floods, which resulted in four casualties and more than $12.5 billion in damages. The residents of the impacted areas blamed the US Army Corps of Engineers for its sub-optimal decisions in releasing reservoirs (Fernandez 2019).

These events have undermined the public trust in reservoirs' performance with respect to flood control (Razavi et al. 2020; Vahedifard et al. 2021). Substantial expenses are made on construction and maintenance of flood-control reservoirs. Yet, inaccurate forecasting of reservoir inflows and faulty operation of reservoirs' gates and spillways result in an increase in peak floods in the downstream areas, and thereby, magnifying flood damages (Dhumal et al. 2022).

There is an urgent need to reduce the intensifying impact of faulty reservoir operation during floods (Vahedifard et al. 2021). This highlights the increasing significance of scrutiny and assessment of reservoir operation after flood events to enhance our understanding of human errors in reservoir operation and develop appropriate policies to reduce the negative impacts of reservoir operation during future floods (Zarei et al. 2023). Therefore, it is vital to develop approaches to evaluating reservoir operation during floods. Previous studies have reported approaches to flood-control reservoir operation (Tanhapour et al. 2025; Wu et al. 2025; Zhou et al. 2024). However, few of these approaches incorporate practical limitations in reservoir operation, and this limits their ability to validate operational policies and to investigate the contribution of management decisions to flood intensification. Furthermore, most of these approaches focus on flood control only during the stage of rising-flood. This restricts their ability to evaluate reservoir operation comprehensively in meeting the conflicting targets of flood control, water conservation and hydropower generation across the pre-flood, rising-flood, and post-flood stages.

It is imperative to address key aspects of past flood events to prevent or mitigate the hazardous consequences of future hazards (Zarei et al. 2021b), such as discerning (i) the factors that have contributed to worsen the hazards, (ii) the role of humans in affecting the magnitude of the hazards, and (iii) the actions that must be taken to reduce the adverse effects of such flood hazards in the future. Forensic engineering is an approach to addressing these questions by applying technical principles to uncover human actions, management anomalies and structural factors that have contributed to damages caused by hazards (Noon

2000; Zarei et al. 2021b). Insights gained from forensic investigations of past hazards can assist in the search for clues to provide an effective alternative strategy for dealing with future hazards and avoiding their adverse impacts. Many authors have applied the forensic engineering approach to investigate damages caused by earthquakes (Barone and Di Maggio 2018), hurricanes (Klepac and Cleary 2022), and fires (Kulkarni et al. 2013) in recent decades. Yet, only few studies have focused on the forensic analysis of hydrologic hazards. The dramatic increase in fatalities and economic losses caused by floods in many parts of the world in recent years have led some authors to focus their attention on forensic studies to mitigate the increasing flood risk. For example, Loaiciga (2001), Bronstert et al. (2018) and Tegos et al. (2022) have applied forensic engineering to identify the governing factors during floods in terms of river hydraulics and hydro-meteorology. Furthermore, considering the intensifying impact of reservoir operation on floods, Zarei et al. (2023) proposed a forensic-engineering framework for the evaluation of reservoir operation under floods. Specifically, the latter authors developed a novel Standard Operation Policy (which is called the Forensic SOP (FSOP) in this study) for reservoir operation to assess the reservoirs' performance during the 2019 floods in Karkheh basin, Iran. However, there are no previous studies focusing on the forensic investigation of the role of reservoirs in flood control applying machine learning (ML) and optimization.

This study proposes approaches for the forensic assessment of reservoir operation for flood protection using ML-streamflow forecasting and optimization. There are multiple works published in the field of reservoir operation for flood control (Beygi et al. 2012; Bozorg-Haddad et al. 2008; Fallah-Mehdipour et al. 2011, 2013; Orouji et al. 2013; Shokri et al. 2012; Soltanjalili et al. 2011), many of which employed advanced approaches. Such analyses can yield more accurate evaluations because of the highly-specialized approaches applied. Nevertheless, reservoir operators may argue that these improved results do not necessarily prove deficiencies in their operation policies, but, rather, reflect the greater computational capability of the advanced approaches compared with the simpler tools available to them during real-time flood management. This study shows, however, machine learning (ML) and evolutionary algorithms (EAs) can be implemented as practical and computationally efficient tools for flood-control reservoir operation, offering both simplicity and interpretability while enhancing decision support.

ML models have been widely applied to hydrological modeling to extract useful patterns from mega data (Babaee et al. 2021; Elbeltagi et al. 2022; Singh et al. 2024; Zarei et al. 2021a), while offering ease of use and rapid implementation. Furthermore, ML models can be applied when hydrologic and meteorological data are sparse and with limited detail and spatial coverage. Support vector machine (SVM) model (Vapnik 1995) is one of the widely-used ML models (Asif et al. 2025; Zhang and You 2024). Parisouj et al. (2020) examined capability of three models of SVM, Artificial Neural Network with backpropagation, and Extreme Learning for forecasting monthly and daily streamflow of four rivers in the United States. The results showed the superiority of SVM to the other models. Zarei et al. (2021a) compared the performance of SVM, Regression Tree, Genetic Programming, and Artificial Neural Network models in forecasting inflows to Karkheh, Dez, and Gotvand reservoirs during the 2019 floods in Iran. Their study's results showed that SVM was among the superior models by conducting an in-depth analysis of the forecasting capabilities of these models using one- and two-month time-lags.

In parallel, there has been a growing interest in employing EAs to achieve the most efficient operation of reservoirs for flood control (Tegegne and Kim 2020; Wahyuni et al. 2024). EAs have proven excellent performance in optimizing reservoir operation during floods (Carmona-Paredes et al. 2023), owing to their ability to improve solution accuracy by enhancing global-search strength, by accelerating convergence and their capacity to solve complex problems of large dimensionality, of non-convex structure, and with discrete representation compared to non-linear programming and dynamic programming methods (Kumar and Yadav 2022). Among EAs, the Genetic Algorithm (GA) (Holland 1992) has gained significant attention from researchers (Hu et al. 2016; Nazari and Kerachian 2024; Tayfur 2017). SeethaRam (2021) employed the Genetic Algorithm (GA) to optimize operation of a multi-target reservoir. The results proved the exceptional performance of GA in optimal operational planning of reservoirs. Moreover, Almubaidin et al. (2024) applied GA for optimal water allocation from reservoirs. The results demonstrated its superiority over historical operation.

By integrating SVM and GA, this study proposes FOOA. This approach applies a rolling-horizon approach that updates inflow forecasts and sequentially adapts operation policy to them in the remaining time of year, ensuring that HO is evaluated under the same evolving conditions that operators faced. This enables FOOA to compute optimally-adaptive release rules that cover the pre-flood, rising-flood, and post-flood periods. This renders FOOA suitable for forensic scrutiny and more effective for planning reservoir operation. Furthermore, FOOA considers the practical limitations in real-world operation of reservoirs by including detailed operating instructions of each reservoirs' gates. It also provides guidance on the operation of reservoirs without spillway gates by informing operators of the optimal time to close the spillway chutes with stop logs during floods. Another advantage of FOOA is that it only requires reservoir inflow data to forecast inflows during the water year, making it viable in developing countries afflicted by data scarcity. Another approach that this study presents is GAA for the optimal operation of flood-control reservoirs under perfect forecasting of reservoir inflows. This enables the application of GAA to evaluate the capacity of reservoirs for flood attenuation. FOOA and GAA are developed in this study to evaluate reservoir operation in Karkheh basin, Iran, during the 2019 floods. Other contributions of this study are: (1) comparing the results obtained by FOOA with those of FSOP in the forensic analysis of reservoir operation during the 2019 floods, (2) conducting sensitivity analysis of the results calculated by FOOA and GAA, and (3) analyzing the reliability and vulnerability of flood control according to different damage thresholds (DTs).

2 Methodology

This study involves developing and implementing FOOA and GAA to reveal if and how reservoir operation could have been modified during floods. Figure 5S (see Supplementary Information) outlines the process of the forensic workflow for assessing historical flood-control operation.

2.1 The Simulation-Optimization Model for Flood Control (SOFC)

The simulation-optimization model for flood control (SOFC) used by both FOOA and GAA- links a simulation model with an optimization model to guide the operation of reservoir gates for flood control. This model optimizes the performance of a multi-reservoir system across the three flood stages (pre, during, and after) for the purpose of flood detention, while preserving sufficient storage for water conservation and hydropower generation. By encoding practical operating limitations, the proposed approaches enable the evaluation of historical policies under real-world conditions. Details on the simulation and optimization models for flood control are provided in Supplementary Information.

GA was applied to develop this optimization model, with population sizes of 200–300, crossover probabilities of 0.6–0.7, mutation probabilities of 0.001–0.01, and stopping criteria of 1000–2000 iterations. These parameters were selected to achieve the minimum value of the fitness function. The roulette wheel selection (Holland 1992) was also applied because it provided better results than other selection operators.

2.2 The Forensic Optimal Operation Approach (FOOA)

FOOA evaluates historical reservoir operation by combining a forecasting method with the SOFC. A ML model forecasts reservoir inflows during the water year, allowing the SOFC to anticipate flood magnitude and schedule pre-releases in the remaining time prior to floods. Monthly forecasts guide operation until the flood announcement period (FAP)—defined as the period during which the SOFC prescribes releases larger than the safe release (SR) to mitigate ML-forecasted floods. Forecasting and optimization shift to a daily time step to enhance responsiveness during the FAP. The monthly and daily procedures along with Figs. 6S and 7S are described in Supplementary Information.

2.3 The Goal Attained Approach (GAA)

GAA is formulated in this study as a benchmark operating model that assumes perfect knowledge of future inflows. It follows the same operational structure as FOOA but replaces forecasted inflows with the observed hydrograph over the water year. Using the SOFC with perfect information reveals the maximum hypothetical performance of the reservoirs under ideal decision-making. This knowledge, in turn, provides a reference point for forensic-engineering investigation of historical operation.

This approach allows the analysis to distinguish between shortcomings caused by operational and forecasting errors and those arising from structural limitations, such as decreased damage thresholds (DT) downstream of reservoirs due to floodplain encroachment or reservoir configurations that lack the capacity to mitigate extreme events. Thus, GAA clarifies whether full flood mitigation would have been attainable under flawless operation.

2.4 Forensic Quantitative Criteria

Forensic evaluation of reservoir performance during floods requires quantitative criteria that reflect both flood management and water conservation and hydropower generation over the water year. Two categories of criteria are used:

1. System-level criteria: reliability, resiliency, and vulnerability for flood control (Delpasand et al. 2021), water conservation, and hydropower generation (Zarei et al. 2023).
2. Reservoir-level criteria: The desirability of reservoir operation (DRO) (Zarei et al. 2023), assessing each reservoir's ability to satisfy its operational targets.

This work assigns weights to the targets of the multi-reservoir system and its components using the weighted least squares procedure in the evaluation of the historical operation during flood, (Chu et al. 1979).

3 Case Study

This study focuses on Seimare–Karkheh reservoir system located in southwestern Iran, where Karkheh basin extends over approximately 51,643 km². Karkheh river originates in Gamasiab headwaters and flows for about 875 km before discharging into Hoor-al-Azim wetland (Fig. 4S in Supplementary Information). Reservoir characteristics are summarized in Table 1S (see Supplementary Information). The Abbas-plain gate is on right bank of Karkheh reservoir, which supplies irrigation water to Abbas plain's agricultural lands.

Long drought shaped reservoir operation policies in the decade preceding the 2019 floods, which aimed at keeping storage high and encouraging land-use expansion within flood-prone zones. Upstream agricultural development led to the non-installation of spillway gates on Seimare reservoir to avoid submerging these areas, reducing its flood-control capacity by roughly 925 MCM (1 MCM$=10^6$ m^3) during the 2019 floods. These land-use changes also substantially lowered the safe release (SR) and significant destructive release (SDR) which severely constrained reservoir pre-releases.

Iran experienced three extreme flood events affecting most of the country in the Spring of 2019. The second and third events occurred in Mar. 24–26 and Mar. 31-Apr. 2, respectively, causing extensive economic damage and human losses in the southwest, including Karkheh basin (Zarei et al. 2021a). Whether the resulting disaster reflected unavoidable hydrologic extremes or deficiencies in operational planning and infrastructure remains a central question. This study evaluates the performance of Seimare–Karkheh reservoir system during the 2019 floods, and examines the implications resulting from such evaluation for future flood-management strategies.

4 Results and Discussion

This study implements FOOA and GAA to evaluate the performance of individual reservoirs and the two-reservoir system in Karkheh basin during the 2019 floods. Figure 5S (see Supplementary Information) shows the 2018–2019 reservoir inflows and mean long-term monthly inflows based on the Iranian calendar. The two-reservoir system and Karkheh reservoir operating targets prioritize water conservation, flood mitigation, and hydropower generating, respectively. However, flood mitigation is Seimare reservoir's top priority, followed by meeting downstream water demands and hydropower generation. Thus, flood mitigation, water conservation, and hydropower generation weights are 35, 45, and 20% for the two-reservoir system, 51, 30 and 19% for Seimare reservoir, and 40, 45, and 15% for

Karkheh reservoir. Seimare and Karkheh reservoirs had maximum power plant performance coefficients of 95 and 97%, respectively, in long-term operation.

4.1 Developing FOOA

Table 2S and 3S (see Supplementary Information) present the results of SVM-based monthly inflow forecasts for Seimare and Karkheh reservoirs corresponding to ten reservoir-inflow projections in the testing phase. The results show that SVM has lower accuracy in forecasting reservoir inflows during flood-prone months (Jan. 21–Feb. 19 to Apr. 21–May 20) compared to other months, as indicated by the performance indices. Forecasting accuracy of SVM improves by increasing the projections' number.

Figure 5S illustrates the forecasted inflows to Seimare and Karkheh reservoirs during 2018–2019 under the ten projections (see Supplementary Information). SVM largely underestimates inflows to Seimare reservoir under projections 1–4 (Fig. 6Sa in Supplementary Information) and to Karkheh reservoir under projections 1–3 (Fig. 6Sb in Supplementary Information). The SOFC accordingly increased Karkheh reservoir storage during projections 1–3 by prescribing lower releases (Figs. 7Sa–c in Supplementary Information). Using projection 4, however, SOFC calculated releases exceeding the SR during Feb. 20–Mar. 20 to Apr. 21–May 21 by (i) applying the maximum power-plant performance coefficient, (ii) releasing surplus discharge through the Abbas Plain gate, and (iii) opening the spillway gate (Fig. 7Sd in Supplementary Information). These months were therefore identified by the SOFC as the flood announcement period (FAP). Tables 2S and 1S (see Supplementary Information) list the performance indices obtained from SVM daily forecasts corresponding to the FAP for Seimare and Karkheh reservoirs in the testing phase.

4.2 Forensic Assessment of HO's Performance in Flood Control

Figures 5S and 5S (see Supplementary Information) present the release and initial storage rules for Seimare and Karkheh reservoirs under HO, FOOA, and GAA. GAA was implemented from Nov. 22–Dec. 21 and applied daily during the flood-announcement period (FAP). Four damage thresholds (DTs) expressed as the multiples of the safe release (SR), or 1.0×SR, 1.5×SR, 2.0×SR, and the significant destructive release (SDR) were used to evaluate flood control under HO.

The reservoirs experienced several small and medium floods and severe floods on Jan. 21-Feb. 19 prior to major floods in Mar. and Apr. Under HO the environmental demands of Seimare River in Sep. 23-Oct. 22 and Oct. 23-Nov. 21 and downstream demands of Karkheh in Oct. 23-Nov. 21 and water demands of the Abbas plain in Sep. 23-Oct. 22 through Jan. 2-Feb. 19 were unmet (Figs. 8Sa and 9Sa–b). These measures were among precautionary operational measures aimed at increasing water-supply reliability during the dry season after a decade of drought. However, such conservative measures de-emphasized the reservoirs' function in controlling extreme floods (Figs. 8Sb and 9Sc). After the Jan. 21-Feb. 19 floods, only 9% of Karkheh's detention zone remained empty, and just 1% was released in Feb. 20-Mar. 20. Table 2S (see Supplementary Information) summarizes other results corresponding to HO, FOOA, and GAA, including Seimare power-plant shutdowns under HO in Sept. 23-Oct. 22 and Mar. 21–24. Figure 1 shows the forensic evaluation of Seimare–Karkheh system's flood-control performance.

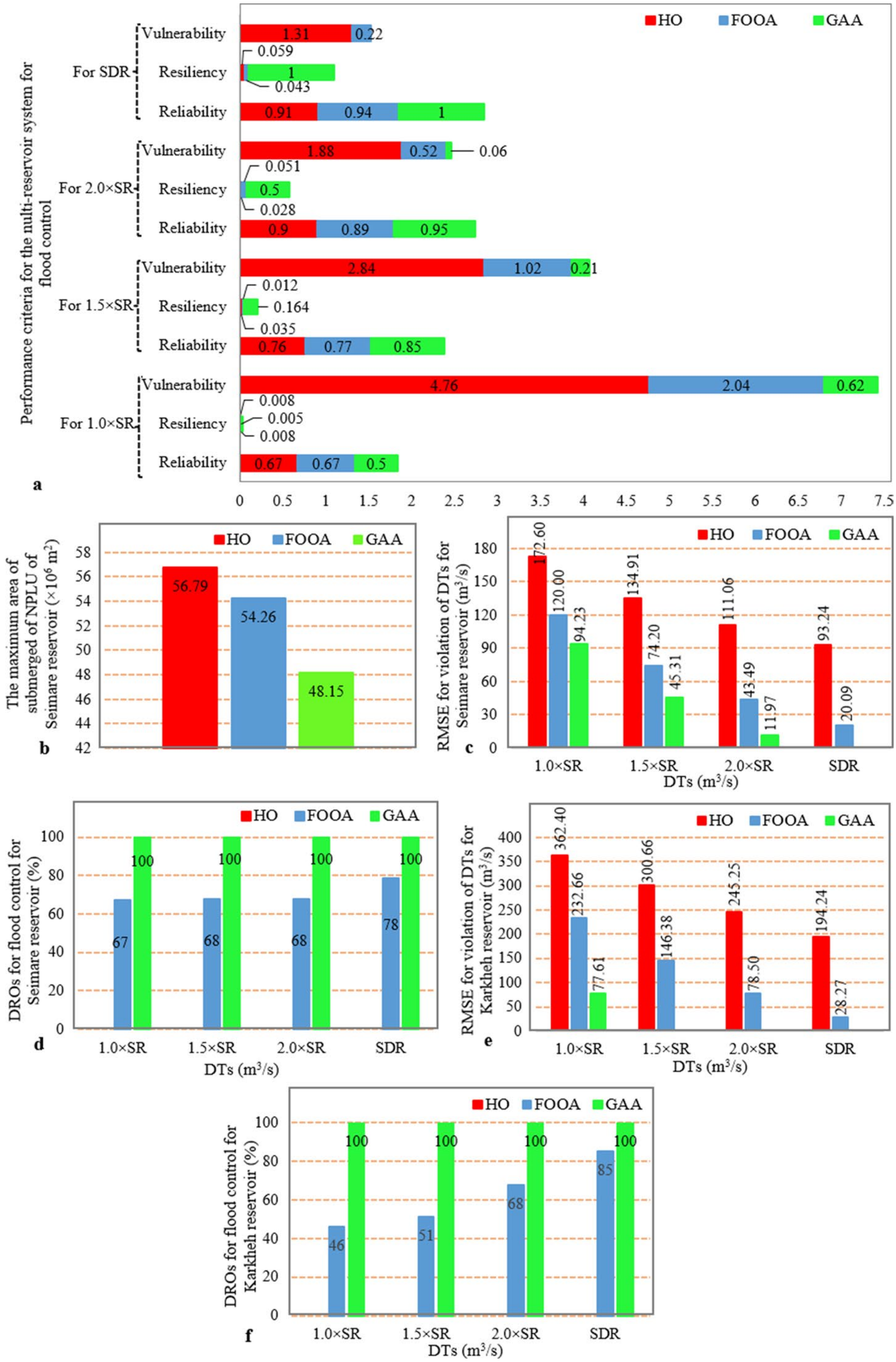

Fig. 1 Results of the forensic evaluation of HO's flood- control function

4.2.1 The Two-reservoir System

Figure 1a shows that concerning 1.0×SR, the performance of the reservoir system in flood attenuation under HO and FOOA is identical in terms of reliability (0.67) and resiliency (0.008). However, under GAA, these criteria are about 17 and 3% lower than HO's, respectively. In contrast, vulnerability to downstream damages under HO (4.76) is roughly 57 and 87% higher than FOOA's and GAA's, respectively.

HO performs worse in flood attenuation concerning the 1.5×SR, with reliability of 0.76 and vulnerability of 2.84—about 1 and 9% lower reliability and 7.5 and 36% higher vulnerability than FOOA and GAA, respectively. However, the resiliency under HO (0.035) is slightly higher than FOOA's by 2.3% but lower than GAA's by 13%.

For 2.0×SR, the system under HO has reliability of 0.90, which is 1% higher than FOOA's but 5% lower than GAA's. However, HO's resiliency (0.028) and vulnerability (1.88) are poorer, being 2.5 and 47% lower in resiliency and 72.5 and 97% higher in vulnerability than FOOA's and GAA's, respectively.

HO according to the SDR exhibits reliability of 0.91 and vulnerability of 1.31, about 3 and 83% worse than FOOA's and 9 and 100% worse than GAA's. The resiliency under HO (0.059) is 1.5% higher than FOOA's but 94% lower than GAA's.

4.2.2 Seimare and Karkheh Reservoirs

Seimare reservoir was operated during 2018–2019, to reduce flood peaks by retaining inflows within its available detention zone while avoiding the submergence of non-possessed lands upstream (NPLU). Thus, alongside flood mitigation and dam safety, protecting NPLU was another key management target. However, during the 2019 extreme floods, operators inevitably prioritized flood control by accepting partial inundation of agricultural areas.

It is seen in Fig. 1b that the maximum submerged NPLU under HO reached 57×10^6 m², which exceeded those under FOOA and GAA by approximately 5 and 15%, respectively. Consequently, FOOA achieved upstream safety outcomes second only to GAA.

The results shown in Fig. 1c indicate that Seimare reservoir under HO experienced RMSEs of 172.6, 134.9, 111, and 93.2 m³/s for the violation of 1.0×SR, 1.5×SR, 2.0×SR, and SDR thresholds. These violations were in ranges 31–78% and 45–100% compared to FOOA and GAA, respectively. Likewise, Fig. 1d indicates that DROs under HO was 67–78% lower than FOOA and 100% lower than GAA. Overall, GAA yielded the most effective flood attenuation for Seimare reservoir, followed by FOOA and HO. The higher detention capacity across all approaches were resulted from closing one of the spillway chutes with a stop log. Nevertheless, even with GAA, avoiding release violations of 1.0×SR and 2.0×SR was not feasible because of Seimare reservoir's restricted storage caused by the non-operational spillway gates.

It can be seen in Fig. 1e that Karkheh reservoir under HO recorded the highest RMSEs—for violation of 1.0×SR through SDR—which were reduced by 36–85% under FOOA and 78–100% under GAA. Similarly, Fig. 1f shows that HO provided the lowest DRO values, being 46–85% smaller than FOOA and 100% smaller than GAA across all DTs. These outcomes confirm that GAA achieved the strongest flood-mitigation efficiency, with FOOA ranking second. The results also suggest that the limited storage of Seimare reservoir led to unavoidable discharge exceedances at Karkheh reservoir corresponding to 1.0×SR, even with perfectly known and optimal releases under GAA.

4.3 Forensic Assessment of HO's Performance in Meeting Water Demands

Figure 2 presents the forensic evaluation of the system and its individual reservoirs in water conservation under HO, FOOA, and GAA.

4.3.1 The Two-reservoir System

Figure 2a shows that FOOA and GAA perform equally in water conservation. The system's reliability, resiliency, and vulnerability under HO are 0.59, 0.006, and 0.34, respectively—about 24, 1, and 0% worse than those of FOOA and GAA.

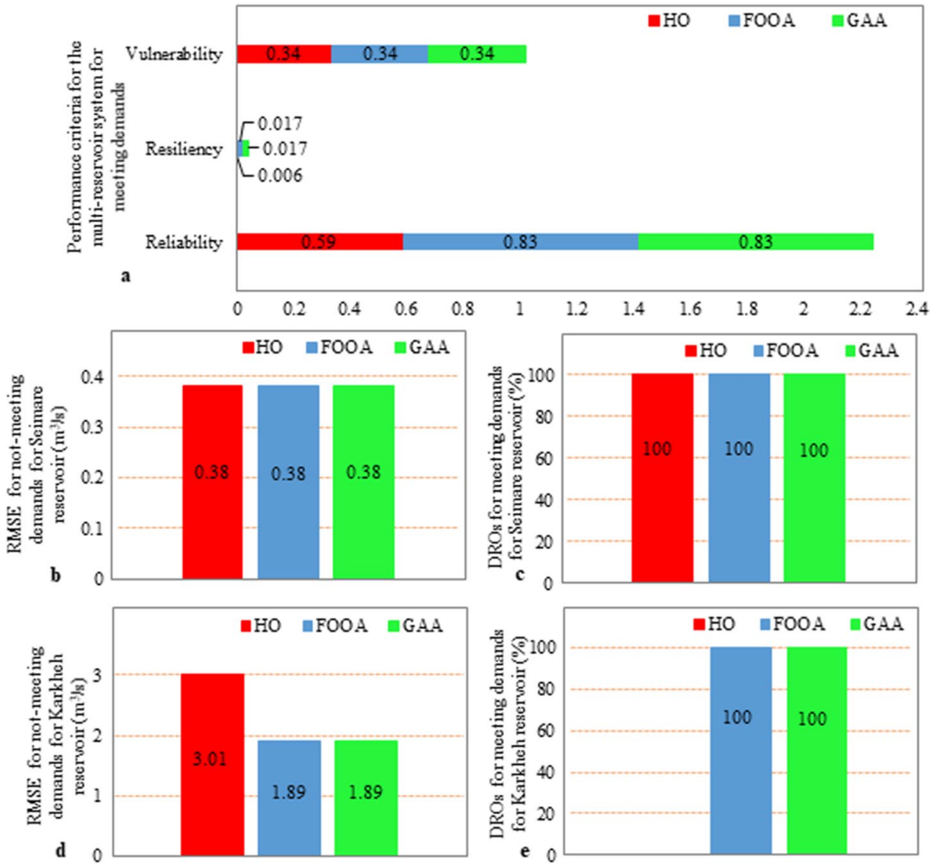

Fig. 2 Results of forensic evaluation of HO's function of meeting water demands

4.3.2 Seimare and Karkheh Reservoirs

The RMSE and DRO values (0.38 m³/s and 100%) for Seimare reservoir, are identical across all three approaches (Figs. 2b–c), indicating equivalent performance in meeting environmental demands.

In contrast, Karkheh reservoir under HO shows a 63% higher RMSE for unmet demands (Fig. 2d) and a complete (100%) reduction in DRO relative to FOOA and GAA (Fig. 2e), confirming HO's weakest performance in satisfying downstream and Abbas plain water demands.

4.4 Forensic Assessment of HO's Performance in Hydropower Generation

Figure 3 illustrates the forensic analysis of the system and its reservoirs in hydropower generation under the three approaches.

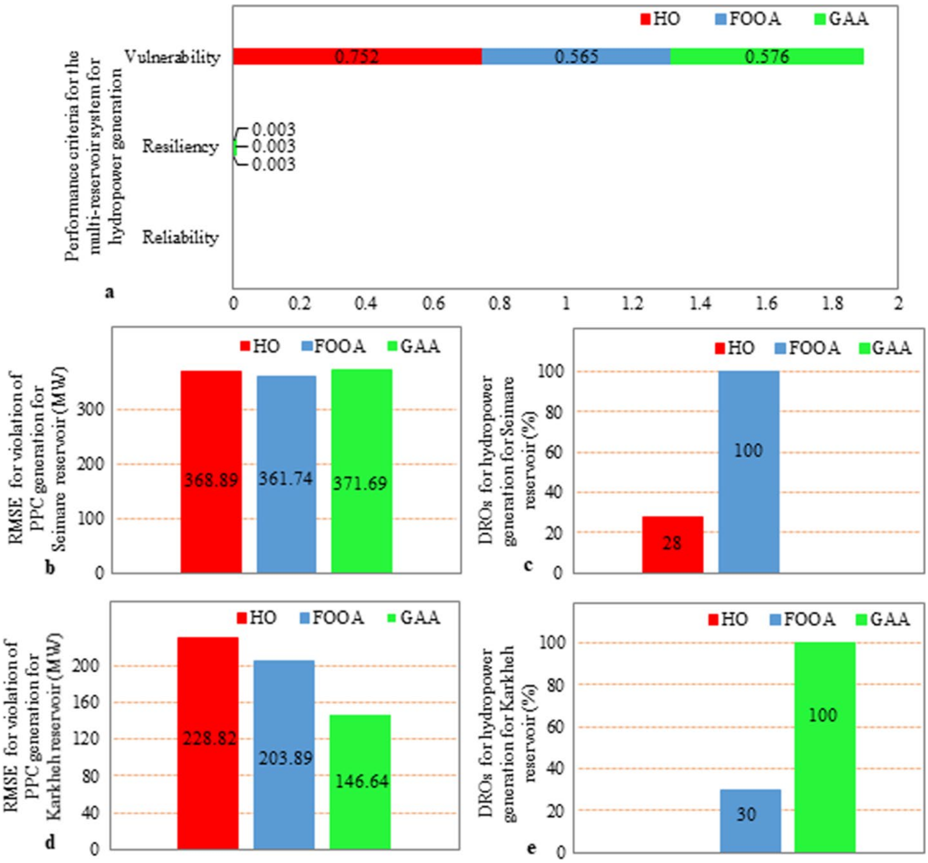

Fig. 3 Results of forensic evaluation of HO's hydropower generation function

4.4.1 Two-reservoir System

All days are failures for hydropower generation during the entire water year because Seimare reservoir could not retain sufficient water for power plant capacity (PPC) due to uninstalled spillway gates. Consequently, the maximum power-plant performance coefficient under both FOOA and GAA was lower than 100%, and system's reliability with respect to PPC generation remained zero under all approaches. The resiliency (0.003) was also equal for all cases, but the vulnerability under HO (0.75) was roughly 25 and 23.5% higher than FOOA and GAA, respectively (Fig. 3a).

4.4.2 Seimare and Karkheh Reservoirs

The RMSE of PPC non-generation under HO is 368.9 MW for Seimare reservoir, about 2% higher than FOOA and 1% lower than GAA (Fig. 3b). It is seen in Fig. 3c that HO's DRO is 72% lower than FOOA but 28% higher than GAA, implying that GAA curtailed hydropower generation to enhance flood-control performance by shutting down the power plant for 34 days before the Mar. 31–Apr. 2 precipitation.

The largest RMSE for Karkheh reservoir (228.8 MW) corresponds to HO, which is 11 and 36% higher than FOOA and GAA, respectively (Fig. 3d). HO also shows the lowest DRO—30 and 100% lower than FOOA and GAA (Fig. 3e).

Figure 4 summarizes the overall performance of the multi-reservoir system under weighted operational targets. Relative to FOOA, HO performs worse in terms of reliability, resiliency, and vulnerability by 22, 83, and 50% concerning 1.0×SR and by 19, 100, and 54% concerning 2.0×SR. FOOA outperforms HO in terms of reliability and vulnerability by 21–53% concerning 1.5×SR and 19–55% concerning SDR, though HO achieves slightly higher resiliency by 33 and 4% concerning 1.5×SR and SDR, respectively.

GAA shows lower reliability and resiliency than FOOA (by 11 and 10%, respectively) concerning the 1.0×SR threshold, but exhibited substantially lower vulnerability (a 51% improvement over FOOA). Nonetheless, relative to HO, GAA improves reliability, resiliency, and vulnerability by approximately 10, 67, and 76%, respectively.

GAA outperforms both alternatives concerning the 1.5×SR: HO trails GAA by 26 (reliability), 312 (resiliency), and 74% (vulnerability), while FOOA is 5, 450, and 45% worse than GAA on the same criteria.

HO's strategy concerning 2.0×SR, differs from GAA by about 22% in reliability, 1323% in resiliency, and 70% in vulnerability, while the corresponding gaps between FOOA and GAA are 3, 611, and 35%.

GAA raises system's reliability, resiliency, and vulnerability for the SDR, by 22, 1408, and 64% versus HO, and by 3, 1474, and 20% versus FOOA. Overall, the operational gap under major floods is smaller between FOOA and GAA than between GAA and HO, indicating the superiority of SVM's forecasts and SOFC's decisions over the forecasting skill and operating rules embodied in HO.

The evaluation of the reservoirs operated individually indicates that Seimare reservoir achieved only 35% of its targets under HO, while FOOA improved these by 48–54% and GAA by 45% concerning the DTs. Hence, For Seimare reservoir, FOOA is the most effective operational strategy under floods, providing the most satisfactory attainment of all targets. DRO results for hydropower generation show GAA is less desirable than FOOA,

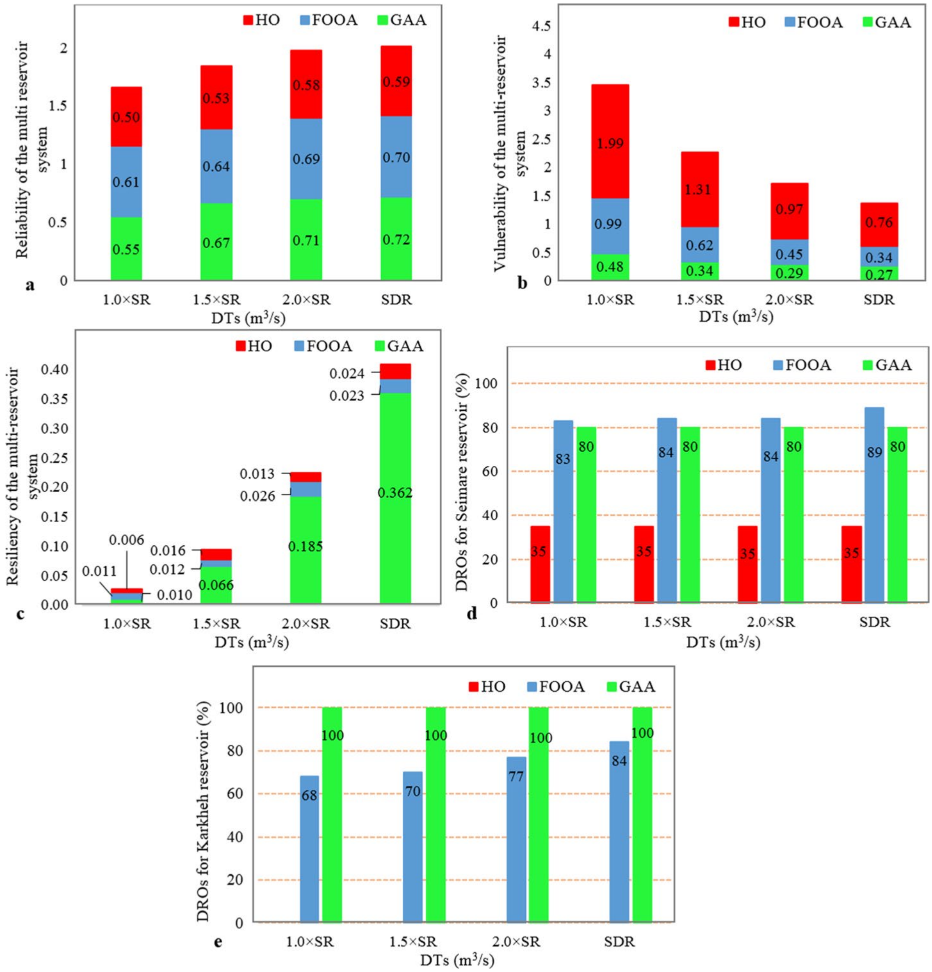

Fig. 4 Results of forensic evaluation of HO's function of achieving all the targets

yielding FOOA advantages of 3, 4, 4, and 9% concerning 1.0×SR, 1.5×SR, 2.0×SR, and SDR, respectively (Fig. 4d). HO shows the poorest results for Karkheh reservoir, performing 68–84% worse than FOOA across thresholds (Fig. 4e). Management policies under HO differ entirely (100%) from GAA, while FOOA differs by only 16–32% from GAA.

4.5 Sensitivity of the Superiority of FOOA and GAA Over HO with Respect to the Targets' Weights

A sensitivity analysis was conducted to examine how the changes in weights of flood control, downstream demands, and hydropower generation influence the average superiority of the approaches over HO. Sensitivity analysis along with Table 3S can be found in Supplementary Information.

4.6 Comparison of the Results Obtained by FOOA and FSOP

According to Zarei et al. (2023), the FSOP is a reliable forensic-assessment approach. It possesses the essential qualities of a forensic tool, including comprehensibility, easy implementation, and accounting for practical limitations in real-world reservoir operations. Therefore, the results obtained from FOOA were compared with those of FSOP to evaluate FOOA's performance for assessing reservoir operation during the 2019 floods. This comparison along with Table 4S are available in Supplementary Information.

The findings of this study align with previous studies that highlight the importance of integrating machine learning and optimization tools in enhancing the performance of flood-control reservoirs (Guo et al. 2020; Tanhapour et al. 2025). However, this study extends current knowledge by showing how such tools can be applied in data-sparse and operationally constrained conditions. This study also supports recent studies to use post-flood analysis for improving flood management in the future (Borga et al. 2019; Romali et al. 2025; Yulianto et al. 2025).

4.7 Analysis of the Behavior of Reliability and Vulnerability Corresponding to Flood Control According to the Damage Thresholds (DTs)

To further investigate reservoir flood-control performance, the behavior of system reliability and vulnerability was analyzed across different flood-damage thresholds (DTs). Please refer to Supplementary Information.

5 Conclusion

Floods are among the most frequent and destructive natural hazards worldwide. The inadequate performance of reservoirs in recent events has renewed attention to their potential role in intensifying flood impacts. This study introduced two novel approaches—FOOA and GAA—for the forensic assessment of reservoir operation during floods. The approaches were applied to analyze the historical operation of Seimare and Karkheh reservoir system during the 2019 floods.

The results showed that HO's performance could have been improved by roughly 50% for Seimare reservoir and by 75% for Karkheh reservoir compared to FOOA, while differed from GAA's ideal operation by 45 and 100%, respectively. The results showed that a more desirable performance in pre-releasing reservoirs and mitigation of 2019 floods without compromising water conservation and hydropower generation could have been possible by improving the forecast accuracy of inflows and optimal reservoir operation. However, under-estimation of inflows under HO led to overly cautious pre-releases in a futile attempt for reliable water conservation and hydropower generation in the dry season, leaving insufficient detention capacity for the March–April 2019 floods.

GAA's partial inability to protect downstream areas further confirms that full flood mitigation was constrained by the limited structural capacity of reservoirs by having experienced a prolonged drought. Particularly impactful in limiting infrastructure's potential in flood control were the floodplain encroachment, the absence of spillway gates on Seimare reservoir, and the significant decrease in damage thresholds.

This paper's findings established that FOOA is a more viable forensic-engineering approach than FSOP, with average desirability improvements of 29.8 and 8.5% for Seimare and Karkheh reservoirs, respectively. FOOA's capacity for forensic assessment of reservoirs' performance during floods demonstrates that it would serve as an effective guidance to judge historical operation, and as a means for improving decision-making and planning for reservoir operation during floods.

List of Acronyms

DRO	Desirability of Reservoir Operation
DT	Damage Threshold
FAP	Flood Announcement Period
FOOA	Forensic Optimal Operation Approach
GA	Genetic Algorithm
GAA	Goal Attained Approach
HO	Historical Operation
MAE	Mean Absolute Error
MGL	Minimum Generation Level
ML	Machine Learning
NPLU	Non-Possessed Lands Upstream
SOFC	The Simulation-Optimization Model for Flood Control
PMF	Probable Maximum Flood
PPC	Power Plant Capacity
R	Correlation Coefficient
RMSE	Root Mean Square Error
SDR	Significant Destructive Release
SR	Safe Release
STL	Spill Threshold Level
SVM	Support Vector Machine

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Declarations

Ethics Approval All authors accept all ethical approvals.

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