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OPTIMIZATION OF MULTI -CONSTRAINT RESERVOIR SYSTEM: A CRITICAL REVIEW OF THE CHARGED SYSTEM SEARCH ALGORITHM

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Abstract

The growing complexity of reservoir management driven by hydrological uncertainty and sedimentation has led to increased reliance on advanced optimization techniques. This review critically examines the recent application of the Charged System Search (CSS) algorithm in addressing nonlinear, multi-constraint challenges within water resource systems. Across the literature, CSS is recognized as an effective method for optimizing operations related to hydropower, water supply, and sediment management. Most studies adopt scenario-based modeling with stochastic hydrological inputs to enhance system resilience under climate variability. A key distinction among studies lies in algorithm customization. While some apply standard CSS, others hybridize it with techniques like Particle Swarm Optimization (PSO), *Sequential Quadratic Programming (SQP), and Genetic Algorithms (GA) to improve convergence and solution quality. Comparisons with other metaheuristics such as Differential Evolution (DE), Ant Colony Optimization (ACO), and NSGA-II further contextualize CSS's relative performance. The reviewed works vary in modeling scale and objectives: some aim to maximize water or energy yield, others to minimize sedimentation or manage operational trade-offs. Models span single- and multi-reservoir systems, with temporal scopes ranging from short-term operations to long-term sediment dynamics. Implementation environments include MATLAB, Python, and specialized hydrological platforms, reflecting methodological diversity. Additionally, researchers employ both single- and multi-objective optimization, often utilizing Pareto fronts for trade-off analysis. By synthesizing these methodological trends and algorithmic adaptations, the review underscores CSS's flexibility and effectiveness within metaheuristic-based reservoir optimization. However, it also identifies key limitations, including a lack of standardization, minimal real-world application, and weak integration with real-time forecasting tools. The paper concludes with suggestions for future research aimed at enhancing computational efficiency, operational relevance, and decision-support capability in the context of increasing water resource challenges under climate change.*

Keywords: Charged System Search (CSS), Reservoir Management, Optimization Algorithms, Sediment Accumulation, Multi-objective Modeling

I. Introduction

Sustainable reservoir management is a serious issue that is being faced in the field of water resources in the world due to growing water line constraints and sedimentation problems, as well as the influence of changing climatic conditions (Ma et al.)(M. A. Almubaidin et al.). The complexity of the current reservoir systems is increasing and requires designing a higher level of computing approaches that would be able to address non-linearities, multi-objective trade-offs, as well as long-run uncertainty (Müller et al.)(Ibrahim et al.). Part of them are metaheuristic optimization approaches, recently known as potent mechanisms to handle conflicting aims of reservoirs and the avoidance of failure of supply of water, generation of energy, flood control at a reservoir, and handling of sediment. The recent developments in the Charged System Search (CSS) are a physics-based metaheuristic algorithm that emulates the dynamics of the interacting particles governed by the Coulomb law of interaction. The model started attracting attention because of their powerful global search and convergence properties. CSS has found some successful use in the solution of different engineering problems, and its ability to optimize reservoir operation in the presence of sediment accumulation is progressively evaluated in modern literature. The capability to reproduce diverse hydrological processes with a complex workflow in the algorithm, and at the same time, including physical and operational constraints, presents a great advantage of the algorithm compared to conventional optimization methods. Fig. 1 presents the structure of optimization of reservoir management based on CSS.

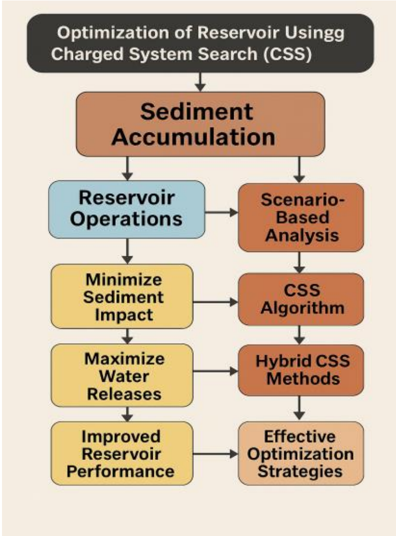

Fig. 1. Optimization framework of reservoir management using CSS.

One of the first attempts of the CSS algorithm application to the optimization or the reservoir operation with specific attention to the sediment deposit was provided by several authors (Ma et al.)(M. A. A. Almubaidin et al.). They concluded that multi-scenario planning is essential due to the non-stationary nature of sediment inflow and to hydrological variation. In the developed research, an optimization framework having multiple objectives based on CSS was developed with references to the objectives of sediment deposition and operating objectives, including water release, storage conservation, and energy generation. The results showed that the CSS-based method proved better than the classical algorithms in reducing a possible accumulation of sediments and ensuring operational resilience, which confirmed its applicability to long-term reservoir sustainability. The hydrodynamic implications regarding reduced performance because of sediment buildup are also demonstrated in the recent works (Goharian et al.),(Lee et al.), (Ummah), which study the wear out of the water level-storage functions (because of gradual loss in storage capacity). Their study was able to rebuild and alter the stage-storage curves by the impact of sedimentation and was able to measure its influence on decisions to control flooding. Though it is not a study concentrated on CSS, the research highlights the necessity to add sediment dynamics to the optimization schemes. Their approach also contains the logic that the operation that is grounded on the old reservoir geometry-based policies is inefficient and that more adaptive methods that are data-informed, like CSS, should be used.

In addition to this, some of the research studies the spatial variation of sediment deposits of the river-reservoir system based on geophysical methods (Obialor et al.) (Latif et al.). The studies provided an understanding of the effects of non-uniform distribution of sediment on reservoir hydraulics and proposed that considering the heterogeneity in the computer modelling can be used to optimize calculations. It was recommended that the characterization of habits and stronger integration of physical characterizations and algorithmic optimization be adopted, and that the use of site-specific models is indeed necessary in a CSS application. Beyond sedimentation, dynamic control of suspended sediment loads in water infrastructure has also been an active area of research. Other studies (Ren et al.)(Kosasaeng and Kangrang) proposed a novel output feedback control system for regulating suspended sediment concentrations in reservoirs and canals. While the focus was not on optimization per se, their work highlights the importance of intelligent control strategies in tandem with optimization algorithms. Their adaptive control scheme can serve as a complementary component to CSS-based optimization frameworks, especially in real-time sediment mitigation.

From a methodological standpoint, outstanding works (Lai et al.) (Shirgir et al.) laid a foundational contribution by applying CSS to jointly optimize hydropower and water-supply operations. Their case study demonstrated how CSS can efficiently handle complex multi-objective formulations, offering high-quality Pareto-optimal solutions. This research not only validated the algorithm's applicability to water resource systems but also reinforced its relevance to multi-scenario analyses that involve environmental, operational, and sedimentation constraints. Collectively, these studies point to a growing consensus on the value of incorporating sediment dynamics and multi-scenario evaluation into reservoir operation frameworks. The convergence of CSS optimization, hydrological modelling, and sediment characterization represents a promising direction for enhancing the resilience and sustainability of reservoirs. However, despite its demonstrated advantages, the use of CSS remains limited in the context of sediment-informed reservoir design and policymaking. There exists a pressing need to review, classify, and critically evaluate the current body of literature to identify knowledge gaps, best practices, and potential directions for future research.

Accordingly, this review aims to provide a systematic and thematic synthesis of recent advances in reservoir optimization using CSS, with an emphasis on sediment accumulation and multi-scenario decision-making. By integrating insights into modelling, algorithm development, and case study applications, the review seeks to answer the following key questions:

- How has the CSS algorithm been adapted to account for sedimentation in reservoir systems?
- What are the dominant scenarios and operational objectives considered in CSS-based studies?
- How does CSS compare with other metaheuristic or classical approaches in terms of performance and adaptability?
- What are the methodological limitations and opportunities for hybrid approaches involving CSS?

The remainder of this review is structured as follows: Section 2 presents a comprehensive literature synthesis, highlighting the evolution of optimization techniques in reservoir management. Section 3 details the methodological characteristics of CSS and its variants. Section 4 focuses on the specific mechanisms and case applications through which supra-harmonic sediment dynamics are integrated into CSS frameworks. Section 5 concludes with recommendations for future research and implementation pathways.

II. Literature Synthesis

The most recent research on reservoir management using the CSS algorithm demonstrates a few similar methodological trends and a few significant differences in the application domain. A common trend that is present in the literature reviewed has been the use of CSS as a metaheuristic algorithm for solving complex, nonlinear optimization models of water resource allocation, hydropower generation, and sedimentation control. All the studies follow a scenario-based modelling framework, usually with stochastic hydrological inputs, to evaluate the extent of robustness in the models used in the optimization. Despite the common methodology, some stark differences are seen in terms of implementation and definition of the problem. Others have used the basic CSS algorithm, whilst some have been able to optimize its performance by incorporating it with additional optimization methodologies like the Particle Swarm Optimization (PSO), the Sequential Quadratic Programming (SQP), or the Genetic Algorithms (GA). Such hybridizations are done to enhance the speed and accuracy of convergence. Goals are also not identical in different studies; some lean towards maximizing the yield of the reservoir and energy production, some towards reducing the accumulation of sediments, and some towards a trade-off between conflicting objectives. Another point of discretion is system scale. Some of the models are applied to single reservoir systems and are constructed such that they have a short-term operational costs attitude, while others take the multi-reservoir view that encompasses long-term sediment dynamics. Also, computational systems vary, and CSS algorithms are applied with tools such as MATLAB, Python, or hydrological-specific modelling programs. Other works aim to address multi-objective optimization, which provides Pareto-optimal solutions, whereas some works keep it single-object formulation that allows one operational objective. Together, these differences show how CSS is flexible and adaptable to the different problems in the management of reservoirs, as well as to illustrate the importance of individualized optimizing strategies driven by a particular hydrological, ecological, and operational setting. The conceptual flow chart of literature synthesis of the recent works is given in Fig. 2.

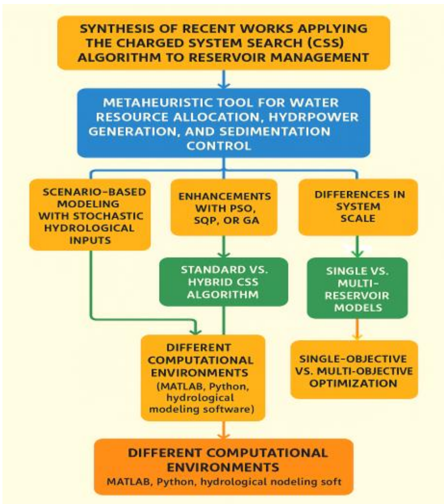

Fig. 2. A diagram showing literature synthesis

Table 1: Comparison of Selected Studies on Reservoir Optimization using CSS.

Ref.	Objective	Methodology	Benchmarked results	Limitations
(Adeyemo and Stretch)	Optimize water distribution design using CSS to minimize costs while meeting demand and pressure.	Applied CSS to minimize water network costs by simulating charged particle movements for optimization.	CSS algorithm found low-cost solutions for benchmark water networks. Outperformed other methods in cost and speed. Achieved near-optimal results with fewer evaluations.	Tested on benchmarks only, sensitive to parameters, with high computational demands, and limited robustness analysis.
(M. A. Almubaidin et al.)	Develop optimal operating rule curves for a reservoir using seven meta-heuristic algorithms.	applying optimization algorithms, generating rule curves, and evaluating performance through validation and sensitivity analysis	All seven methods outperformed the current strategy; TLBO performed best overall.	Includes model simplifications, limited uncertainty, algorithm bias, and no climate change integration.
(M. A. A. Almubaidin et al.)	To optimize the Mujib reservoir operations under sedimentation, water demand, and storage scenarios using CSS	Applied CSS algorithm with MUSLE model for sediment estimation; scenario-based simulation with reliability metrics	Water deficit reduced by up to 53.59% under combined sediment removal, demand reduction, and storage increase.	Lack of consistent sediment data; challenges in monthly sediment simulation
(Asadieh and Afshar)	To test CSS for water supply and hydropower optimization of the Dez reservoir	Applied CSS over 3 operation periods (60, 240, 480 months); benchmarked against GA, ACO, PSO, and NLP.	CSS outperformed traditional and heuristic methods in convergence and solution quality	Limited to a single-reservoir model; it does not account for sediment dynamics.
(Chou et al.)]	Optimize water and energy use in Vietnam's multi-reservoir system.	Used GWASIM with BOBYQA to optimize multi-reservoir operations.	Improved water use and power generation.	Did not account for climate change or sediment impacts.
(Dahal et al.)	Use HEC-HMS and HEC-RAS to predict how sediment deposits in the KCMP reservoir over decades. Measure resulting storage loss to inform sustainable	Used HEC-HMS for runoff and sediment inflow modelling. Used HEC-RAS (1D) to simulate how sediment deposits in the KCMP reservoir over time.	Sedimentation causes up to 32.5% storage loss in 100 years at KCMP. Sediment mostly builds up upstream.	The study relies on simplified 1D modelling with limited data, leading to reduced accuracy and long-term results based on assumptions rather than real-time validation.

	reservoir planning in Nepal.			
(El Harraki et al.)	To optimize reservoir operating rules using a genetic algorithm with a new objective function and smoothing constraint.	GA optimized operating rules with a new objective and smoothing.	GA improved reservoir operation efficiency and smoothed release patterns.	May require careful tuning of GA parameters; applicability tested on a single case study.
(Goharian et al.)]	Optimize the Aswan Dam using ML, water balance, and policy trees for changing conditions.	Uses ML, simulation, and policy-tree learning for adaptive dam operations	The model showed good accuracy (NSE/$R^2 > 0.6$), but no direct comparison to other methods.	Concerns include data reliability, climate projections, model complexity, and limited generalizability.
(Ibrahim et al.)	Review of methodologies for reservoir optimization.	Systematic review of 24 studies on metaheuristic algorithms for reservoir optimization using PRISMA.	Metaheuristics improve reservoir optimization but have some challenges.	Limited real-world testing and high computational demands.
(Jahandideh-Tehrani et al.)	Introduce and review PSO in water management.	Summarized PSO applications for optimizing water management.	PSO improves water management optimization.	PSO may get stuck in local optima and requires careful tuning.
(Kaveh and Talatahari)	Introduce and develop the Charged System Search optimization algorithm.	Models' particle movement uses electric forces for optimization.	CSS performs well, often beating other algorithms.	Needs tuning and may be slow on large problems.
(Kosasaeng and Kangrang)	Optimize reservoir operations using hybrid metaheuristic algorithms	Applied CASO and CGA to optimize multi-reservoir operations.	The hybrid algorithms improved efficiency in multi-reservoir operations.	High computational cost and complex parameter tuning.
(Lai et al.)	Optimize reservoir operation using metaheuristic algorithms and identify the best method through a real dam case study.	Applied FA, ABC, and SFLA to optimize TEMENGOR Dam releases, minimizing errors and comparing performance.	SFLA was fastest and most accurate; ABC was good but slower; FA was least efficient.	Tested on one reservoir only; no sediment modelling; future conditions not considered.

(Lai et al.)	Study and compare methods for reservoir optimization.	Test metaheuristic algorithms on reservoir models and compare results.	Metaheuristics improved reservoir operations.	Algorithm performance depends on parameters; it may require high computation time.
(Latif et al.)	Use CSS to optimize Klang Gates Dam releases, reduce shortages, compare with other methods, and enhance sustainability.	CSS effectively optimized reservoir policies, reducing deficits and outperforming traditional methods.	CSS outperformed other metaheuristics in optimizing Klang Gates Dam releases, minimizing deficits, and boosting reliability.	CSS shows promise but needs broader testing, complex modelling, and real-world validation.
(Lee et al.)	To assess long-term sedimentation effects and downstream impacts from desilting operations	Used CIR and CSR indices and hydro morphological modelling for sediment impact analysis	With desilting projects, 70.3% of initial storage can be retained vs. 32.9% without	High sediment concentration risk during flushing; site-specific to SHIHMEN
(Ma et al.)	To reconstruct WLS curves considering sedimentation and assess flood regulation risk	Developed capacity loss rate (LR) index; applied flood regulation simulation to a 9-reservoir cascade	Significant WLS underestimation: up to 7.11 m Z* and 3% γ	Dependent on historical sediment records; applicability limited to large-scale systems
(Motlagh et al.)	Optimize TALEGHAN Dam reservoir operation using Grey Wolf and Genetic Algorithms and compare their performance.	Used Grey Wolf and Genetic Algorithms to optimize reservoir releases based on historical data.	Grey Wolf Optimization outperformed Genetic Algorithms in speed and accuracy, providing better reservoir operation policies for TALEGHAN Dam.	Single reservoir; no sediment or climate factors; real-time use not tested.
(Müller et al.)	Different inflow and outflow sequences affect the rate of suspended sediment exchange in reservoirs.	Lab experiments with basins to test inflow/outflow effects on sediment.	Inflow/outflow patterns significantly impact sediment exchange rates.	Lab-scale setup may not fully represent real reservoir conditions.

(Niu and Shah)	The overarching goal is to **optimize reservoir planning and operations** using an **economic life-cycle perspective,** where sedimentation and decommissioning are treated as core design considerations, not afterthoughts.	Economic optimization model; Sediment management considerations; Dam decommissioning Cost; Sensitivity analysis; Illustrative application.	The results highlight the economic importance of incorporating sediment management and decommissioning into reservoir planning, showing that neglecting them significantly lowers reservoir value.	The study presents useful economic insights but is constrained by a hypothetical case, simplified sediment strategies, and limited consideration of broader system dynamics.
(Obialor et al.)	Explain sedimentation causes, impacts, management methods, and stress-integrated solutions.	Reviewed and synthesized literature on reservoir sedimentation without new experiments.	Sedimentation reduces reservoir capacity and affects operations. Mitigation methods help, but need integrated management.	Qualitative review, lacks data, regional focus, long-term monitoring, and specific mitigation details.
(Ren et al.)	The study examines sedimentation in the Three Gorges Reservoir, evaluates management strategies, analyzes upstream trapping effects, and offers recommendations for enhancing reservoir sustainability.	Long-term sediment and flow data from the Three Gorges Reservoir were statistically analyzed to assess deposition patterns and the effectiveness of management strategies such as trapping, regulation, and dredging.	Sediment inflow reduced by ~70% due to upstream trapping and conservation. Sediment deposition in the reservoir is ~33% of the original design estimates. 80–85% of suspended sediment is retained by the Three Gorges and GEZHOUBA dams.	Limited by short sediment records, complex river dynamics, narrow management strategies, minimal climate change consideration, and context-specific findings tied to the Three Gorges Reservoir.
(SaberChenari et al.)	To optimize short-term reservoir operation using PSO.	Optimize release decisions based on objective functions like water supply or hydropower generation.	PSO improved reservoir operation efficiency and met objectives effectively.	PSO may converge prematurely and is sensitive to parameter settings.
(Sun et al.)]	To maximize both water diversion and hydropower using the MOEA/D-AWA algorithm.	Applied MOEA/D-AWA; compared with NSGA-II and original MOEA/D using hyper-volume index	MOEA/D-AWA provided better Pareto solutions than baselines	No sediment consideration; case-specific to HUANGJINXIA reservoir

Shirgir et al.	Minimize the cost and CO2 emissions of a real-size RC bridge via multi-objective optimization.	Non-dominated sorting genetic algorithm II (NSGA-II) with parametric modelling and finite element analysis.	Achieved significant reduction in cost and emissions; optimal designs generated with better trade-offs than traditional methods.	Focuses only on one bridge type; applicability to other structures needs validation; ignores uncertainties like material variation.
(Thomas et al.)	Develop an optimal reservoir operation for climate adaptation	Applied optimization under climate scenarios.	Improved reservoir performance under climate change.	Did not include sediment dynamics in the model.
(Trivedi and Shrivastava)	Optimize reservoir operation to minimize irrigation and hydropower deficits.	Hybrid Invasive Weed and Cuckoo Search Algorithm (HIWCSA), tested against standard WOA and CSA on Indira Sagar Reservoir (ISR).	The hybrid model improved performance by 5–9% over individual methods; reduced water deficits by 62% over the study period.	Study limited to one reservoir; needs testing across different hydrological and climatic settings; lacks real-time implementation.

III. Theoretical Concept of CSS Algorithm

The CSS algorithm is a metaheuristic optimization technique rooted in the fundamental principles of electrostatics and Newtonian mechanics. It belongs to the family of nature-inspired algorithms, utilizing the metaphor of charged particles interacting in a physical space to guide the search for optimal solutions. CSS is especially suited for nonlinear, multi-modal, and constrained optimization problems, making it ideal for applications such as reservoir operation planning, where complex interdependencies and competing objectives exist.

- *Initialization and Charge Assignment*

CSS starts with N agents (particles), the representatives of the possible solutions to the search space with a dimension n. The location of the i^{th} agent of iteration t is represented as:

$$\vec{x}_i^t = \left(x_{i1}^t, x_{i2}^t, \dots, x_{in}^t\right) \quad (1)$$

The fitness function is predetermined to evaluate each agent $f(\vec{x})$ based on this fitness, and a charge q_i is given to each agent, which represents the quality of the solution. One of the most popular charge determination formulas is:

$$q_i = \frac{f_{worst} - f_i}{f_{worst} - f_{best}}, \ for\ f_{worst} \neq f_{best} \quad (2)$$

where:

- $f_i = f(\vec{x}_i)$ is the fitness of the i^{th} agent,
- f_{best} and f_{worst} are the best and worst fitness values in the current population, respectively.

This will make superior solutions (lower f_i) have more charge value.

- *Electrostatic Force Calculation*

The algorithm used by CSS is a simulation of the Coulomb law, according to which every two charged particles will attract or repel each other. The force $\vec{F}_{ij}$ is the force put on agent *i* by agent *j* as:

$$\vec{F}_{ij} = k \cdot \frac{q_i q_j}{\|\vec{x}_j^t - \vec{x}_i^t\|^2 + \epsilon} \cdot \frac{\vec{x}_j^t - \vec{x}_i^t}{\|\vec{x}_j^t - \vec{x}_i^t\|} \tag{3}$$

where:

- κ is a constant analogous to Coulomb's constant,
- ϵ is a small positive value to avoid division by zero,
- $||\,.\,||$ denotes the Euclidean norm.

The forces of all other agents added as vectors give the resulting force on the agent *i*:

$$\vec{F}_i = \sum_{j=1\ j\neq i}^{N} \vec{F}_{ij} \tag{4}$$

- *Motion Dynamics*

The particles are supposed to all have a unit mass. The acceleration a_i^t of the particle *i* at iteration *t* is then:

$$\vec{a}_i^t = \vec{F}_i \tag{5}$$

With the acceleration provided, velocity and the new position of the particle are obtained because of the use of the simplest kinetic equations:

$$\vec{v}_i^{t+1} = r_1 \cdot \vec{v}_i^t + r_2 \cdot \vec{a}_i^t \tag{6}$$

$$\vec{x}_i^{t+1} = \vec{x}_i^t + \vec{v}_i^{t+1} \tag{7}$$

r_1 and r_2 in this case are random numbers that tend to have numbers between zero and one, resulting in the addition of stochastic behavior to increase the ability of global search.

Boundary Conditions and Constraints

Beyond basic repair and penalty strategies, several advanced constraint-handling mechanisms have been applied in reservoir optimization. Feasibility-based rules prioritize feasible solutions to ensure hydrological safety and ecological flows, while adaptive and dynamic penalties progressively tighten constraint enforcement to enhance convergence. Hybrid and multi-population approaches as well as ε-constraint methods further improve search efficiency, although their integration with CSS remains limited. Table 2 summarizes the main strategies, their applications, and reported outcomes in the literature, highlighting the research gap in CSS studies.

Table 2: Summary of constraint-handling strategies in reservoir optimization studies

Authors	Constraint-Handling Method	Application	Key Findings
Adeyemo & Stretch (2018)	Hybrid evolutionary approaches	Review of hybrid algorithms in reservoir optimization	Highlighted the advantages of hybridization to address complex and multiple constraints

Almubaidin et al. (2024a)	Enhanced optimization with penalties	Multi-reservoir system	Developed optimal rule curves under multiple constraints; penalties improved solution feasibility.
Almubaidin et al. (2024b)	CSS is considering sediment-related constraints	Reservoir sediment accumulation	Integrated storage loss due to sediment into CSS optimization; maintained feasible reservoir levels
Goharian et al. (2022)	Policy tree–based rules	High Aswan Dam, Nile River	Incorporated hydrological and safety constraints directly into the decision-tree structure
Ibrahim et al. (2022)	Review of penalty & feasibility-based methods	Literature review on metaheuristics	Identified penalties and feasibility rules as the most common constraint-handling mechanisms in reservoir studies
Kosasaeng & Kangrang (2023)	Hybrid conditional algorithms (Atom Search + GA)	Networking reservoirs	Conditional handling of operational limits improved feasibility but increased computational effort.
Latif et al. (2021)	Penalty functions within CSS	Klang Gates Dam, Malaysia	Applied CSS with operational constraints; penalty terms ensured feasible releases.

Convergence and Stopping Criteria

The algorithm repeats cycles of updating positions and accelerations until a stop criterion is reached. Such common conditions are:

- A maximum number of iterations,
- No improvement in the best solution for a defined number of iterations,
- Achieving a predefined objective function threshold.

The CSS algorithm mimics the interaction of physical charged particles to explore and exploit a complex solution space. Through dynamic updates driven by electrostatic principles and Newtonian motion, it offers a robust framework for solving constrained and multi-objective problems. Its flexibility and extendibility (e.g., CSS-GA, CSS-PSO hybrids) allow it to be tailored to specific applications, including reservoir operation under sedimentation and hydrological variability. Fig. 3 and Fig. 4 show the conceptual diagram and the pseudocode description of the CSS algorithm, respectively.

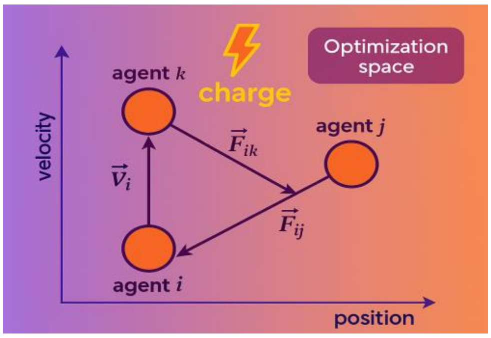

Fig. 3. Conceptual diagram of CSS algorithm.

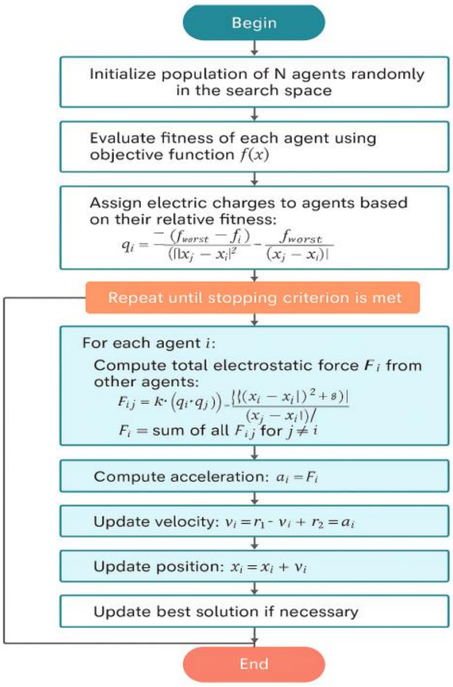

Fig. 4. Flowchart showing the pseudocode description of the CSS algorithm.

Sensitivity and Robustness Analysis in Reservoir Optimization Studies

Most CSS-based and metaheuristic reservoir studies have not systematically examined sensitivity to parameter variations or the robustness of solutions under uncertainty. For example, Latif et al. (2021) applied CSS to Klang Gates Dam without analyzing the effect of parameter changes, while Goharian et al. (2022) optimized the High Aswan Dam without testing policies under stochastic inflows or demand variability. Similarly, Kosasaeng and Kangrang (2023) introduced a conditional hybrid approach but did not include robustness tests, and Ibrahim et al. (2022) highlighted this lack of practice across the literature. The absence of such analyses limits confidence in the reported results, suggesting that future research should integrate sensitivity and robustness testing under extreme scenarios such as droughts and floods.

Performance Metrics and Statistical Validation in Reservoir Optimization Studies

Most CSS-based and metaheuristic reservoir optimization studies primarily report performance through convergence plots and final best solutions. However, such reporting does not fully capture the stochastic variability of these algorithms. Table 3 summarizes how different studies have addressed performance metrics and statistical validation. The review shows that while some papers reported average values or multiple runs, only a limited number incorporated rigorous statistical testing, such as Wilcoxon or Friedman tests. This indicates a clear gap in the literature: the lack of standardized reporting of mean, standard deviation, confidence intervals, and significance testing across ≥30 runs, which is essential to establish the robustness and reliability of reservoir optimization results.

Table 3: Reporting of performance metrics and statistical analysis in reservoir optimization

Study	# Runs Reported	Metrics Reported	Statistical Test Used	Notes
Adeyemo & Stretch (2018)	Not specified	Narrative review of hybrid EA methods	None	The review paper highlights the lack of consistent statistical reporting
Almubaidin et al. (2024a)	Not specified	Best solutions, convergence curves	None	Focused on deriving optimal rules; limited statistical evidence
Almubaidin et al. (2024b)	Not specified	Best and average solutions	None	Addressed sedimentation constraints; statistical variability not analyzed
Goharian et al. (2022)	Case study, not repeated	Best solutions only	None	Policy-tree optimization; no statistical tests reported
Ibrahim et al. (2022)	Systematic review	Mean, Std, CI discussed conceptually	Wilcoxon, Friedman (reported in some studies)	Identified need for ≥30 runs and rigorous statistical validation
Kosasaeng & Kangrang (2023)	20 runs	Best, Mean, Std	None	Conditional hybrid approach; reported average performance but no significance testing.
Lai et al. (2022)	Not specified	Convergence plots, best results	None	Comparative study of metaheuristics; lacks statistical rigor
Latif et al. (2021)	20 runs	Best and average solutions	None	CSS applied to Klang Gates Dam; no statistical test used

IV. Results for Sediment Accumulation

Sediment accumulation poses a critical threat to reservoir functionality by reducing effective storage capacity and impacting operational performance. Among the reviewed studies, two works, [Ma et al 2025.] and [Almubaidin et al 2024.], present indepth quantitative analyses on sediment deposition and its consequences, while others either neglect sedimentation or address it tangentially. Ref. [Almubaidin et al 2024] conducted a comprehensive simulation of sediment accumulation in the Mujib reservoir using the Modified Universal Soil Loss Equation (MUSLE). The study revealed that by the end of 2019, 14.6% of the reservoir's capacity had been lost due to sedimentation. The authors demonstrated that removal of accumulated sediment could reduce the water deficit by 19.42%, and when combined with a reduction in agricultural water demand by 11%, the deficit dropped further by 42.40%. This underscores the major operational improvements achievable through sediment management strategies. Furthermore, increasing the reservoir's storage by 30% in addition to sediment removal and demand reduction led to a 53.59% reduction in water deficit, showcasing the synergistic benefits of integrated strategies. [Ma et al 2025.] investigated the impact of sediment accumulation on flood control and storage curves in a cascade of nine reservoirs in China's WUJIANG River. The authors reconstructed the water level-storage (WLS) relationship based on observed sediment-induced capacity loss. Notably, the Suofengying reservoir experienced a 25.02% loss in storage capacity, the highest rate in the study, while the HONGJIADU reservoir recorded the largest absolute loss, at 180.3 million m^3. Using outdated WLS curves, flood control risks were severely underestimated. The maximum flood regulation level (Z^*) was off by up to 7.11 meters, and risk exceedance periods (γ) by up to 3%, especially at longer return intervals. These findings strongly emphasize the necessity of updating operational models to reflect current sediment realities. Other studies: [Lee et al 2022.], [Latif et al 2021], and [Thomas et al 2021] did not quantify sediment accumulation in the same detail. While sediment management was acknowledged in broader discussions of operational efficiency and reservoir optimization, no explicit models or metrics on volume loss or its operational impact were presented. Their focus leaned more on hydropower optimization, water supply, or general system modelling.

Table 4: Comparison of Sediment Accumulation Results

Ref.	Reservoir / Study Area	Sediment Accumulation Results	Operational Impact	Notes / Limitations
(M. A. A. Almubaidin et al.)	Mujib Reservoir, Jordan	14.6% storage loss due to sediment accumulation	Water deficit reduced by up to 53.59% with sediment removal, demand reduction, and storage expansion.	Monthly sediment simulation challenges; lack of consistent data

(Ma et al.)	WUJIANG River Cascade, China	Up to 25.02% capacity loss (Suofengying); 180.3 million m³ lost (HONGJIADU)	Flood regulation level underestimated by 7.11 m; exceedance period γ underestimated by 3%	Results dependent on historical sediment data; focused on the large-scale system
(Lee et al.)	SHIHMEN Reservoir, Taiwan	Without desilting: only 32.9% capacity retained; with desilting: 70.3% retained	Desilting significantly improved storage retention	Site-specific findings: high sediment concentration risk during flushing
(Latif et al.)	Dez Reservoir, Iran	Not assessed	Focus on water supply and hydropower optimization	Sediment dynamics are not considered
(Thomas et al.)	HUANGJINXIA, China	Not assessed	Multi-objective optimization for diversion and power	Sediment accumulation was excluded from analysis

V. Conclusions

This review emphasized three critical aspects in the optimization of multi-constraint reservoir systems using the Charged System Search (CSS) algorithm. First, **sediment accumulation** has been shown to cause substantial capacity loss in reservoirs such as Wujiang (25.02%) and Mujib (14.6%), directly affecting water availability, flood regulation, and sustainability. Integrated sediment management strategies, including desilting and adaptive demand reduction, have proven effective in mitigating shortages and enhancing long-term operational efficiency.

Second, most reviewed CSS-based studies rely primarily on **basic penalty or repair functions** to address operational constraints, while more advanced methods—such as feasibility rules, adaptive penalties, hybrid, and ε-constraint approaches—remain underutilized. This reveals a methodological gap in the literature.

Third, the reporting of **performance metrics and statistical validation** is often insufficient. While convergence plots and best solutions are frequently presented, only a few studies systematically report averages, standard deviations, confidence intervals, or apply non-parametric tests such as Wilcoxon and Friedman. This limits the robustness and comparability of results.

Overall, future research should integrate sediment processes, adopt more sophisticated constraint-handling mechanisms, and apply standardized statistical validation protocols across multiple runs. These improvements will strengthen the credibility and applicability of reservoir optimization studies and support the sustainable management of water resources.

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