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Review

Optimization of Dam Operation and Interaction with Groundwater: An Overview Focusing on Greece

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Abstract: The optimization of dam operations to transform them into multi-objective facilities constitutes a challenge for both hydrology, hydrogeology, and hydropower generation. However, the use of the optimal algorithm for such transformation is critically important. Additionally, the literature has highlighted that dams might negatively influence the recharge of groundwater. Within this study, we provide an overview of the available algorithms for the optimization of dam operations. Additionally, an overview focusing on hydropower generation in Greece illustrates the high potential of the Mediterranean region for hydropower generation and the application of MAR. The water quality of the reservoirs is also highlighted as a critical parameter. Within this study, we present indices for water quality monitoring in dam reservoirs, while the most prevailing index is the SRDD. This study constitutes a guide for researchers in choosing the optimal tools for the optimization of dam operations and the water quality monitoring of reservoirs. The present study suggests a meta-heuristic optimization methodology using the harmony search algorithm. The model uses a geometric model of the reservoir and calculates the level–supply curve. Furthermore, a multi-criteria optimization model was developed with two objective functions: the maximum power output from the hydroelectric power plant turbines and the optimal groundwater recharge. The model with appropriate parameter modifications can be applied to any small dam as it is a decision- and policy-making methodology, independent of local conditions. A further step is the application of these approaches dealing with field data and the numerical modeling of case studies. The interdisciplinary approach of this study links deferent aspect and scientific perceptions, providing a comprehensive guide to optimal water resource management and environmental sustainability.

Keywords: dams; energy; renewable energy; managed aquifer recharge; Greece; harmony search algorithm; meta-heuristic; multi-objective optimization

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1. Introduction

Because of climate change and the growth of the population, reservoirs are assuming a progressively more crucial role in the management of water resources. Reservoirs can be used for multiple purposes, such as municipal and industrial water supply, irrigation, hydropower generation, water quality management, flood protection, recreation, low-flow augmentation, and managed aquifer recharge [1].

Dams can be categorized into three general categories based on their location, which are as follows: (a) hydraulic dams in lakes or rivers [2]; (b) check dams for controlling sediments on land surface [3]; and (c) subsurface dams in coastal zones to prevent seawater intrusion [4].

The regulation of river flow and the use of water resources in a cost-effective and safe way constitutes the main role of dams. The first dams were constructed many centuries ago, before questions and concerns were raised about the environmental changes they cause, and objections to their utilitarian expediency had been raised. The first dams were built mainly to provide flood protection and water storage for irrigation purposes, while in modern times, they were used for hydroelectric power generation, fish farming, tourism, and recreation. Today, dams have different characteristics than other civil engineering structures, are much larger than in the past, utilize knowledge of hydrology and hydraulics, and the magnitude of the direct or indirect, economic or non-economic impact has increased.

Globally, there are more than 50,000 large dams for the management of energy and water [2]. In the Mediterranean region, dams are essential for the sustainable water supply due to the unbalanced distribution of precipitation during the hydrological year. During the wet period of the winter, the reservoirs of dams store the water, while during the dry period of summer, the water is used for energy production and domestic, agriculture, and industrial use. In Greece, more than 150 dams have been built, which range from small to very large (Table S1). In such environments, dams can be used for multiple scopes. The development of optimal operational solutions for multi-scope reservoir systems is often complicated by a multiplicity of conflicting purposes and project uses. The complexity of their operation has also increased, especially in hydropower reservoirs, due to the increasing variability of hydroelectric generation. Handling a multi-reservoir system presents intricacies stemming from factors such as high-dimensional complexities, non-linearities, and the existence of conflicting objectives. The decision-making model incorporates both optimization and hydrological simulation models, creating a fused simulation–optimization approach. The use of optimization techniques has demonstrated remarkable effectiveness in conjunction with simulation modeling, and the synergy between these two methods has consistently yielded optimal outcomes in the realm of reservoir management [5].

Groundwater depletion constitutes a global issue, not just an issue for the Mediterranean region, and has been highlighted in many countries [6]. In some cases, managed aquifer recharge might constitute the main strategy with which to mitigate the phenomenon. The transformation of dams into energy production units and the use of water in order to apply managed aquifer recharge have been suggested as solutions [7].

Nevertheless, such transformation requires a deeper knowledge of the hydrological and hydrogeological regime of the site, and the optimal algorithm for the function of the facility is critically important. Within this study, we provide an overview of applications in the literature of algorithms in multi-scope dams. Considering that managed aquifer recharge by using water from the dam's reservoir requires acceptable water quality, we provide available water quality indices for the characterization of water. Additionally, an analysis of the hydropower generation in Greece is provided and linked with the quantitative and qualitative status of groundwater systems in Greece. The overview and the analysis aim to encourage researchers to test the transformation of small dams into energy production facilities and, simultaneously, apply managed aquifer recharge.

2. Hydropower in Greece

The production of energy through the utilization of the available hydrodynamic potential of an area is a process that has been applied for many years and continues to improve with the development of technology [8]. In Greece, the development of hydropower plants (Figure 1) was historically implemented by the incumbent public power utility. The development by private entities and individuals concerns small-scale projects, and these began in 1994 with the corresponding law that provided for such development projects [9], with the majority of cases concerning projects with a capacity of 0.5 to 3 MW. Usually, such projects are not visible from crowded places because they do not involve significant water collection and storage, nor do they involve the construction of large dams and reservoirs, making them more environmentally friendly [10]. According to the existing legislation of Greece, small hydroelectric stations refer to small units that use watercourses or small dams for electricity production, and their power must not exceed 15 MW [11].

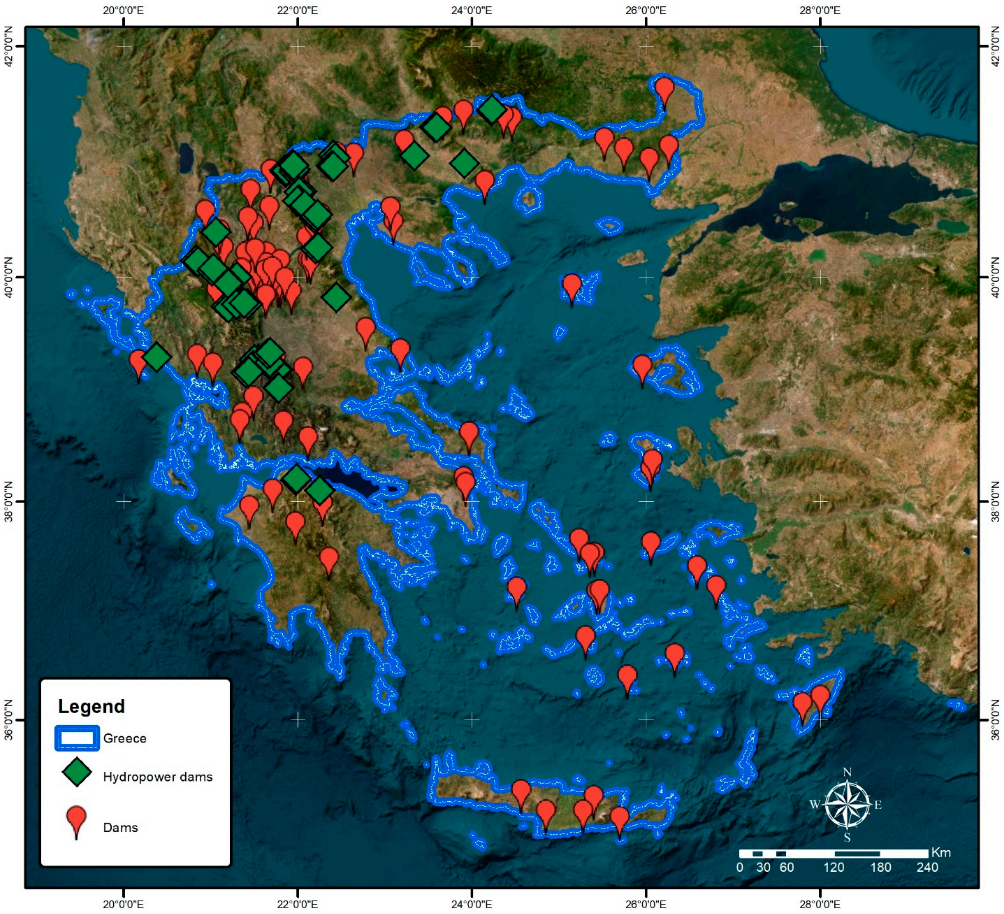

Figure 1. Hydropower plants and dams in Greece.

Moreover, due to the morphology and climate of Greece, hydroelectric plants perform relatively high-efficiency indices [8] with favorable technoeconomic analyses [8,12]. Today, a large part of the energy produced from RES in the world still comes from hydropower [9]. The advantages are significant and, in combination with the increasing demands for more energy, they are becoming even more important [13].

The utilization of the small hydro potential of Greece presents a big gap in the development of RES [14]. According to the European Energy Institute (EEI), in the last 25 years, there have been no initiatives by the authorities to rationalize the institutional framework and exploit the country's small hydro potential, as manifested in other countries. In Greece, the growth rate of the four plants per year is rather low, and it takes many years to reach satisfactory levels [14]. The European Renewable Energy Federation (EREF) has set high goals for increasing RES and reducing gas emissions.

Small hydropower electric plants (SHEPs) have the highest energy efficiency (energy produced per unit of installed power) of all RES technologies. Indicatively, it is stated that the average energy efficiency of SHEPs exceeds 40%, while the corresponding efficiency amounts to 25% for wind and 16% for photovoltaics. According to recent data from PPC (Public Power Corporation), each kWh produced by SHEP is compensated with a price that amounts to about 49% of the average energy price of all RES and about 26% of the average cost of a photovoltaic kWh [11,15].

According to the data of RAE and CRES [9,14], the percentage of utilization of the available hydro potential of Greece does not exceed 12%, while other countries of the European Union have exceeded 70%. In our country, at the moment, 119 projects are operating, with a total installed capacity of 243.9 MW. Moreover, based on RAE data, it appears that the growth of MUS in recent years is minimal and ranges from 3 to 5%. At the moment, the corresponding rate of increase in the installed capacity of other technologies ranged from 19% to 70% (wind–photovoltaic), while the total rate of increase in the capacity of RES reached 43%.

In recent years, efforts have been made to utilize existing hydraulic projects (water supply and irrigation networks, dams, etc.) for energy production, giving a second use to water management [16]. These applications have a high-efficiency index, as they utilize existing infrastructure. Services such as EYDAP, DEYA, and TOEB are some that participate in such development projects in Greece [9,14]. SHEPs can significantly contribute to sustainable regional and local development and also to achieving energy goals. It is imperative to utilize the hydrodynamics of Greece, at least at the average level of European countries.

The small hydro potential of Greece is an environment for the development of many promising projects. Small watercourses in the mountains, water supply and irrigation networks, small dams, etc., are cases where, with proper planning, important energy production projects can be developed. More flexible legislation is needed in cases with faster procedures. RAE already excludes projects smaller than 50 KW from the power generation license.

3. Water Quality in Reservoirs

Dams also serve as water reservoirs for domestic use. Obviously, continuous monitoring and high-quality preservation in the reservoirs are critical issues since water is a fundamental component of human life [17,18]. Commonly, human interference in aquifers, mostly due to irrigation, domestic water supply, or power generation reasoning, results in the construction of artificial reservoirs, changing the hydrological regime and also inducing chemical, physical, and biological changes in the ecosystem [19]. Artificial dams impose many impacts simultaneously, i.e., water temperature increase, eutrophication, thermal stratification, toxicity issues, ecological impacts on downstream rivers and associated wetlands, dissolved oxygen levels, and turbidity alteration in reservoirs that set environmental impact assessments, and follow-up monitoring is a priority [20–22].

Unfortunately, precise predictions of the impacts in a specific dam are extremely difficult due to the individuality and complexity of aquatic ecosystems. Human activities play an important role in how reservoirs are affected due to irrigation, industrialization, urban activities, and climate change [23]. Climate variables such as temperature and precipitation (snow, rain, etc.) may even result in extreme impacts, such as droughts and floods, which, in turn, disturb the balance of the ecosystem. Water temperature and nutrient levels in reservoirs are parameters whose increase causes thermal stratification and eutrophication, a respective decrease in dissolved oxygen, and an increase in the growth of phytoplankton and algae. Even at dams in low latitudes, seasonal fluctuations of lower significance are affected [24,25]. Furthermore, artificial reservoirs' hydraulic retention time (HRT) differs from riverine water, a fact that influences the duration of stratification and evokes particle sedimentation, turbidity decrease, and alteration in biological and geochemical cycles [19,26]. The operation of a dam may also be responsible for increased concentrations of redox-sensitive metals such as iron and manganese [27].

Understanding the potential changes to dam systems is critical for decision-making with respect to their water quality management. To control the aforementioned impacts, action in the operation of dams could be taken. More specifically, the most applied solution is the environmental flows that aim at the approach of the natural hydrologic ecosystem. Other solutions that offer water quality management in the reservoir are mixing aeration or oxygenation that aims at controlling the dissolved oxygen, thermal buffering in order to avoid stratification, and sediment manipulation through spillways or sediment bypass systems [22,28,29]. It is of high importance to collect spatial, temporal, flow, and climate data to monitor damming impacts.

For water quality matters, the framework for the protection of EU waters that was established by the EU 2000/60 Water Framework Directive should be consulted since it establishes an integrated approach to the improvement, protection, and sustainable use of Europe's water (groundwater and surface) [30]. For water quality classification, a valuable means is the relatively new multivariate statistical model of the water quality index (WQI). WQI was initially introduced by Horton (1965), comprising a tool that rates the overall water quality status into a single value (score). Usually, higher scores indicate better water quality (excellent, good), and lower scores indicate degraded quality (bad, poor) [31]. Since then, a plethora of water quality indices have been proposed and applied. WQIs consider general water parameters, such as turbidity, pH, temperature, dissolved oxygen, and NH_3 concentrations, among others. The research of Udin et al. [32] conducted a review of 110 published manuscripts from which they identified 21 WQI models being used globally. It is noticeable that significant differences occur between classifications given by different indices of the same water sample [31].

The variety of WQIs has led researchers either to assess the examined parameters for water quality characterization with more than one index simultaneously, such as in the case of water quality in Polyphytos' reservoir that was examined by Zotou et al. [33], with the comparative performance of seven different WQIs, i.e., Prati's Index of Pollution, Bhargava's Index, Oregon WQI, Dinius' Index, CCME WQI, NSF WQI, and the weighted arithmetic WQI, or to create new WQIs, such as in the research of Lobato et al. [34]. The most commonly applied WQIs are summarized in Table 1. The best-known and most widely used index in the world is the National Sanitation Foundation's Water Quality Index (WQI-NSF) index, which was proposed by Horton [35] and Brown et al. [36]. Moreover, Alexakis et al.'s [17] findings showed that when WQI-NSF was compared to the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI), the classification of the reservoir was closer to that of the WFD-ECOFRAME approach, which is a methodology proposed to define the ecological status of shallow reservoirs.

Table 1. Most applied water quality indices.

WQI	Mathematical Expression	Parameters	Reference
NSFWQI: National Sanitation Foundation Water Quality Index	$\sum_{i=1}^{n} W_i Q_i$	Dissolved oxygen, temperature, pH, BOD, total solids, fecal coliforms, turbidity total phosphate, nitrates	Brown et al. [36]
CCME WQI: Canadian Council of Ministers of the Environment Water Quality Index	$100 - \left[\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right]$	Four quality parameters are required but not specified	Tyagi et al. [37]
OWQI: Oregon Water Quality Index	$\left[\frac{n}{\sum_{i=n}^{n} 1^{1/Q_i^2}} \right]^{0.5}$	pH, dissolved oxygen, faecal coliforms, BOD, chlorate, nitrates	Cude [38]
SRDD: Scottish Research Development Department index	$\frac{1}{100} \left(\sum_{i=1}^{n} W_i Q_i \right)^2$	Temperature, turbidity, total solids, pH, dissolved oxygen, free and saline ammonia, total oxide, nitrogen, phosphate, BOD, *Escherichia coli* (*E. coli*)	Uddin et al. [32]

Where:
n = number of parameters;
W_i = relative weight of the ith parameter;
Q_i = quality rating (subindex value) of the ith parameter;
Scope (F_1) = Number of variables, whose objectives are not met. $F_1 = \frac{\text{No. of failed variables}}{\text{Total no. of variables}} \cdot 100$;
Frequency (F_2) = Number of times by which the objectives are not met. $F_2 = \frac{\text{No. of failed tests}}{\text{Total no. of tests}} \cdot 100$;

Amplitude (F_3) = Amount by which the objectives are not met.

(a) $\text{excursion}_\text{i} = F_2 = \frac{\text{Failed test value}_i}{\text{Objective}_j} - 1$;

(b) normalized sum of excursions (nse) = $\frac{\sum_{i=1}^{n} \text{excursions}_i}{\text{No. of tests}}$;

(c) $F_3 = \frac{nse}{0.01nse+0.01}$.

4. Meta-Heuristic Optimization Algorithms

Operating a dam for energy production is a highly intricate endeavor, typically aided by optimization algorithms. Meta-heuristic algorithms, usually inspired by either natural or artificial processes, such as hydropower generation, emulate the continuous advancement seen in these phenomena to enhance their internal search procedures. Genetic algorithms [39] are perhaps the most prevalent optimization method, simulating the natural evolutionary process in line with Darwin's theory. Numerous techniques grouped under evolutionary computational methods, including evolution strategies, evolutionary programming, and genetic programming, follow the same evolutionary principle. Simulated annealing, a successful algorithm developed in the early 1980s, draws inspiration from the artificial phenomenon of metals recrystallizing during an annealing process [40].

The quest for innovative algorithms in the field of optimization has persisted, leading to the creation of approaches such as particle swarm optimization [41] and ant colonies [42], both inspired by the behaviors of living organisms. In 2001, Geem et al. introduced the harmony search algorithm (HSA), a modern meta-heuristic algorithm inspired by the process of music composition [43]. The HS Algorithm, utilized in this current study, stands out as a potent and efficient tool, boasting a straightforward structure as an added benefit. These features have piqued the interest of professionals in the optimization domain. Initially conceived for the optimal design of water distribution networks [44], HSA has since garnered increasing attention and application in various fields. In the contemporary literature, alongside its application in water engineering optimization, one can discover a wide array of intriguing implementations.

4.1. Harmony Search Algorithm

The harmony search algorithm operates as a stochastic meta-heuristic technique grounded in the iterative generation of potential solutions. It falls within the realm of "local meta-heuristics", generating a single potential solution, referred to as a "harmony", in each cycle. Each prospective solution comprises a collection of values for the decision variables associated with the target function for optimization. Throughout the optimization journey, a quantity of "harmonies" matching the "Harmony Memory Size" is retained within the "Harmony Memory", constituting a repository housing the assembled array of solutions. The optimization procedure concludes once the predetermined total number of iterations has been attained.

4.1.1. Characteristics of the Harmony Search Algorithm

Following the establishment of the decision variables, the harmony memory matrix is constructed. The harmony memory takes the form of an m × n matrix, where m signifies the harmony memory size, and n corresponds to the number of decision variables embedded within the objective function. Subsequently, the algorithm commences the generation and assessment of fresh "Harmonies" by employing the fundamental mechanisms inherent to HSA:

Harmony Memory Consideration: This mechanism draws upon the values of variables already stored in the harmony memory. Its purpose is to ensure that valuable solutions uncovered during the optimization process play a role in enhancing subsequent solutions.

Pitch Adjustment: Constituting the second mechanism of the algorithm, pitch adjustment introduces slight modifications to certain solutions chosen via the harmony memory consideration mechanism. These alterations are executed via selecting neighboring values for the decision variables.

Improvisation: The third mechanism, known as improvisation, introduces novel, random elements into the solutions. The probability of incorporating such random values is equal to (100-HMCR)%. This approach enriches the diversity of solutions available.

Once a new "Harmony" is generated, its performance is evaluated based on the corresponding objective function value. If this performance surpasses that of the least effective "Harmony" stored within the harmony memory, it replaces the inferior one. This iterative procedure continues until the termination criterion is met. A comprehensive depiction of the steps involved in HSA can be found in Figure 2.

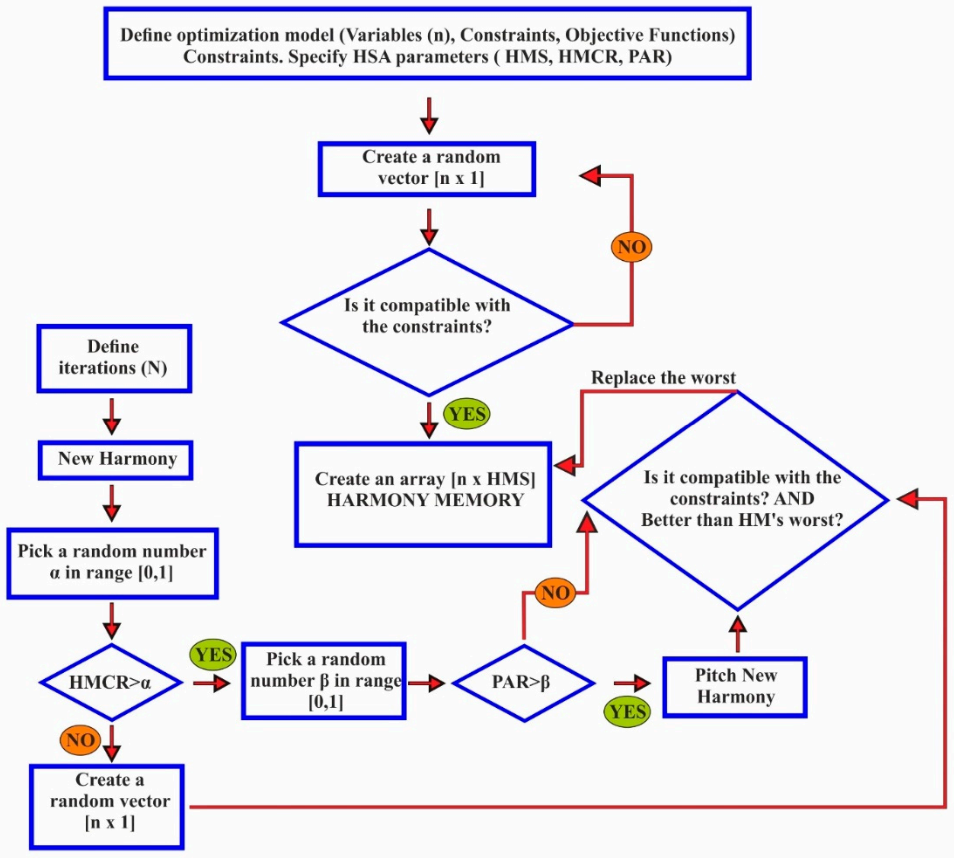

Figure 2. Harmony search algorithm.

4.1.2. Single-Objective and Multi-Objective Optimization

The original harmony search algorithm was initially designed to tackle single-objective optimization problems. Expanding the scope of HSA to encompass multi-objective problems has proven to be a formidable undertaking, as it necessitates a fundamental reconfiguration of its components. Multi-objective problems tend to exhibit intricate structures, conflicting objectives, and the simultaneous optimization of diverse functions, which often poses a formidable challenge. Additionally, the global optimum in the realm of multi-objective problems markedly differs from solutions optimized for individual objectives.

As previously noted, the analysis of multi-objective problems often involves the application of Pareto domination theory. According to this theory, one solution is said to dominate another if it outperforms it in at least one objective function and is at least as good in all other objectives.

In the context of water resources management decision-making, NP-hard problems frequently emerge, characterized by numerous and typically conflicting objectives. Employing exhaustive algorithms to address such challenges demands prolonged computational efforts, which escalate exponentially in correlation with problem complexity. Consequently, employing a non-deterministic approach, while not guaranteeing the identification of optimal solutions (those residing on the Pareto front in multi-objective optimization), provides an efficient and pragmatic avenue for tackling intricate problems. Heuristics and meta-heuristics, such as HSA, offer viable means of addressing NP-hard problems within polynomial time constraints.

5. Application of Meta-Heuristics Algorithms

A state-of-the-art review of mathematical models developed for reservoir operations was studied by Yeh [45]. The authors evaluated the determinist optimization algorithms, including linear programming (LP), dynamic programming (DP), and nonlinear programming (NLP) [45]. A collective study of multi-purpose reservoir optimization was described by Ko et al. [46]; specifically, it evaluated multi-objective optimization methods dealing with the large-scale, nonlinear, dynamic, and stochastic characteristics of multi-reservoir systems. As a case study, the methodologies are applied to the Han River Reservoir System in Korea. The simulation model includes four objective functions: water supply; annual hydropower production; reliable energy generation; and minimization of the risk of violating firm water supply requirements. Stochastic optimization (SO) methods applied on dams are assessed by Labadie JW [47]. In this study, the author describes the application of heuristic programming methods using evolutionary and genetic algorithms along with an application of neural networks and fuzzy rule-based systems for inferring reservoir system operating rules. Chang et al. [48] used meta-heuristic techniques in many complex multi-objective problems related to reservoir operation. Furthermore, Tospornsampan et al. [49] combined the GA and differential dynamic programming approach to optimize the operation of multi-reservoir systems.

During the last decade, comprehensive models combining simulation and optimization have dominated classical optimization methods. This occurred because optimization techniques show high efficiency when used with simulation modeling, and this is the only means of undertaking real-time dam management. Fayaed et al. [5] propose a review study to critically evaluate and analyze simulation, optimization, and combined simulation–optimization modeling approaches and present an overview of their utility in previous studies.

In the literature, there are applications of algorithms for the optimization of dam operation. Cai et al. [50] used genetic algorithms to optimize the dam function for flood control in the Three Gorges dam in China. In Thailand, Tospornsampan et al. [49] and Tospornsampan et al. [51] used algorithms for the optimization of dam operation for irrigation and hydropower production. Ahmadianfar et al. [52] conducted a fuzzy set theory with a genetic algorithm for dam optimization. In the dam of Feitsui and Shihmen in Taiwan, Chang and Chang [48] used a non-dominated sorting genetic algorithm for the multi-objective function for the water supply of industry and local population. Chen et al. [53,54] used particle swarm optimization (PSO) and an adaptive random inertia weight (ARIW) strategy for the optimization of a dam for flood control, water supply, and hydroelectric power in China. Bashiri-Atrabi et al. [55] used the harmony search algorithm for flood management. In Iran, several applications have been recorded for dam optimization for irrigation purposes [56–65]. Li and Lian [66] involved sediment deposition in the optimization of dam optimization for irrigation and hydropower production. Li et al. [67] used dynamic programming (IDP) and a genetic algorithm for flood control and power generation in the Three Gorges dam in China. In India, all studies focused on the optimization of dams for irrigation. Bilal et al. [68] and Reddy and Kumar [69] used hydrological parameters as inputs in the optimization algorithm. Rani and Srivastava [70] involved dynamic programming and genetic algorithms to optimize irrigation and water supply. Jothiprakash and Shanthi [71,72] used a simple genetic algorithm in the Pechiparai dam. In the USA, two applications were found in the literature (articles in journals ranked in Scopus). In the first case, non-linear optimization was used by Dat et al. [73,74], while Hınçal et al. [75] used the genetic algorithm in Blue Mesa dam.

5.1. Harmony Search Algorithm on Dams

Over the past few years, there has been an increasing inclination towards employing the harmony search algorithm to optimize dam systems. Over the last two decades, researchers have extensively applied the HSA to various scenarios, including both standardized benchmark cases and practical reservoir systems. Impressively, the HSA has demonstrated its ability to pinpoint optimal solutions in these contexts. An example of this success can be seen in Geem's work from 2007, wherein he tackled a complex problem involving multiple dam systems. The objective of this project was to optimize the advantages obtained from both hydropower generation and irrigation, a classic multi-objective challenge characterized by competing objectives. Geem's findings revealed that the harmony search model was capable of identifying five distinct global optimal solutions, all of which offered the same maximum benefits regarding the aspects of hydropower generation and irrigation. In contrast, the enhanced genetic algorithm (GA) model, when subjected to the same number of function evaluations, could only uncover near-optimal solutions [76]. In the literature, it is customary to compare new results with older ones, especially in the context of meta-heuristic algorithms, which represent a continuously evolving technology. An enhanced version of this algorithm was introduced by Janatrostami S. et al. for optimizing the Dez dam in Iran [77]. Furthermore, Hasan Torabi et al. developed advanced HSA techniques [78] aimed at optimizing the long-term operation of the Dez dam reservoir (over a 40-year period) with the objective of fulfilling downstream agricultural water requirements. Another study by Bashiri-Atrabi et al. employed the harmony search algorithm (HSA) to address a multi-objective problem related to minimizing water supply deficits and flood damages downstream of a reservoir. To define the flood damage objective function, they harnessed a geographic information system (GIS) database. The results demonstrated that HS exhibited a notable advantage in terms of convergence speed towards an optimal objective function value when compared to alternative techniques such as honey-bee mating optimization (HBMO) and a global optimization model known as LINGO 8.0 NLP solver. This study introduced a comprehensive methodology for modeling reservoir operations, encompassing several key components: data acquisition (including land use, river cross-section, inflow data, reservoir characteristics, and water demands); hydraulic flood routing modeling; the estimation of flood damage functions; and the optimization of reservoir operations using the HS algorithm. Notably, this approach seamlessly integrated the HS algorithm, the HEC-RAS 2010 river hydraulics simulation model, and a geographic information system (GIS). The model was then applied to the Narmab reservoir, a multi-purpose facility located in the Golestan province in northern Iran [55].

A key benefit of the harmony search algorithm (HSA) lies in its adaptability, allowing it to be seamlessly integrated with and enhanced by other optimization techniques. For instance, Van Hoa Ho et al. introduced a hybrid optimization approach that combines HSA with other methods, which they successfully applied to the Huong Dien hydroelectric dam project in Vietnam [79]. Moreover, S. J. Mousavi et al. employed the harmony search optimization algorithm to tackle the complex task of optimizing the design and operation of the Bakhtiari Dam [80]. In a different application, Mohammad R. Hassanvand et al. utilized a multi-criteria decision-making approach with the assistance of the meta-heuristic HSA to select the most suitable spillway type and optimize the dimensions for the Qeshlagh Dam [81]. Kougias et al. developed a user-friendly interface software based on HSA, which is versatile and can be applied across various scientific domains. They specifically applied this software to manage a renewable energy system, focusing on simulating the hydraulic characteristics of a small-scale hydropower station. The HSA toolkit was instrumental in optimizing the SHP station's operations while ensuring compliance with ecological constraints related to environmental flow regimes [82]. Additionally, Milan, Cisty, and Veronika Soldanova introduced an innovative methodology that combines ensemble modeling with data-driven models, leveraging the harmony search algorithm for optimizing the ensemble structure. This approach was utilized to predict inflow patterns into the Daecheong Dam in Korea and mitigate the risk of flooding in landscapes and urban areas, which can lead to substantial damage to infrastructure and human lives [83]. A critical challenge in the management of multi-purpose reservoirs pertains to the non-convex nature of the potential policy space, coupled with the high algorithmic complexity, which is known to be NP-hard. This challenge becomes even more pronounced when employing population-based heuristic methods to address large-scale, real-time multi-reservoir operation problems. The sheer magnitude of variables exponentially intensifies the complexity, necessitating extensive computational time. To tackle this issue, Mohammad Hadi Afshar and colleagues have introduced an innovative approach referred to as cellular automata (CA), designed to efficiently address multi-reservoir hydropower operation problems [84]. In this method, the harmony search (HS) technique is seamlessly integrated into a CA framework. Within this framework, the CA plays a crucial role in decomposing the operation of the extensive reservoir system into a series of smaller-scale sub-problems, with each sub-problem's size aligning with the number of reservoirs within the system. The HS method is then applied to solve each of these sub-problems, with the outcomes subsequently incorporated back into the CA method. To assess the applicability of the harmony method in multi-purpose reservoirs, Mohamed Shams et al. employed the harmony search algorithm (I) in the context of reservoir engineering-assisted history-matching for the Kareem reservoir located in the Amal field within the Gulf of Suez. The study conducted a comparative analysis, pitting the results obtained throuIHSA against those derived from genetic and particle swarm optimization algorithms. The findings provided compelling evidence supporting the superiority and effectiveneIof of HSA [85]. The authors attributed the enhanced perforIce of HSA in addressing reservoir engineering-assisted history-matching queries over other algorithms to the following factors:

- Striking the right equilibrium between exploration and exploitation during the quest for ideal solutions;Ithin the HSA algorithm, the management of solution diversity proves notably superior through the utilization of two sub-elements (alteration of pitch and stochastic elements) in contrast to alternative optimization methodologies;
- The harmonious interplay among the three components (harmony memory preservation, pitch adjustment, and stochastiIlements) in HSA empowers the discovery of impartial solutions;Iplementing the HSA algorithm stands out for its simplicity compared to alternative optimization techniques, largely due to its reduced sensitivity to optimization parameters.

5.2. Conceptual Model

Groundwater availability is, in many areas, at a worrying state. The exploitation of groundwater is facing critical challenges because natural groundwater recharge is a time-consuming process that does not offset the growing rate of groundwater demand. This problem will increase with population growth. Given that reservoirs typically have a surplus of water throughout the annual cycle, it becomes technically feasible to transform an irrigation reservoir into a small hydroelectric power station (referred to as MIS), harnessing the excess kinetic energy. This approach aligns with both water demand requirements and the reservoir's input capacity. Although such hydroelectric facilities may not achieve high levels of efficiency, their construction costs are considerably lower because they repurpose existing infrastructure. Multi-purpose reservoirs can be categorized into two types: those with distinct volumes allocated for each specific use; and those with a unified volume serving all purposes. When converting a single-purpose reservoir into a multi-purpose one, a unified volume is designated to accommodate all potential reservoir functions. However, it is important to note that such dams cannot be employed for flood protection since this function necessitates a low useful volume in contrast to hydroelectric operations, which require a consistently high water level. In most instances, augmenting the reservoir's functionality is essential to expanding its utility volume. The modern trend of optimization is the combination of individual models into a conceptual system. This methodology has three main advantages: (a) it describes the physical problem much better without focusing on individual elements; (b) it enables ecological and social parameters to be included in the decision model; and (c) it allows the model to be optimized in real time. A conceptual model for optimizing reservoir energy production and maximum ecological benefits (managed aquifer recharge) is presented in Figure 3, and the algorithm is presented in Figure 4.

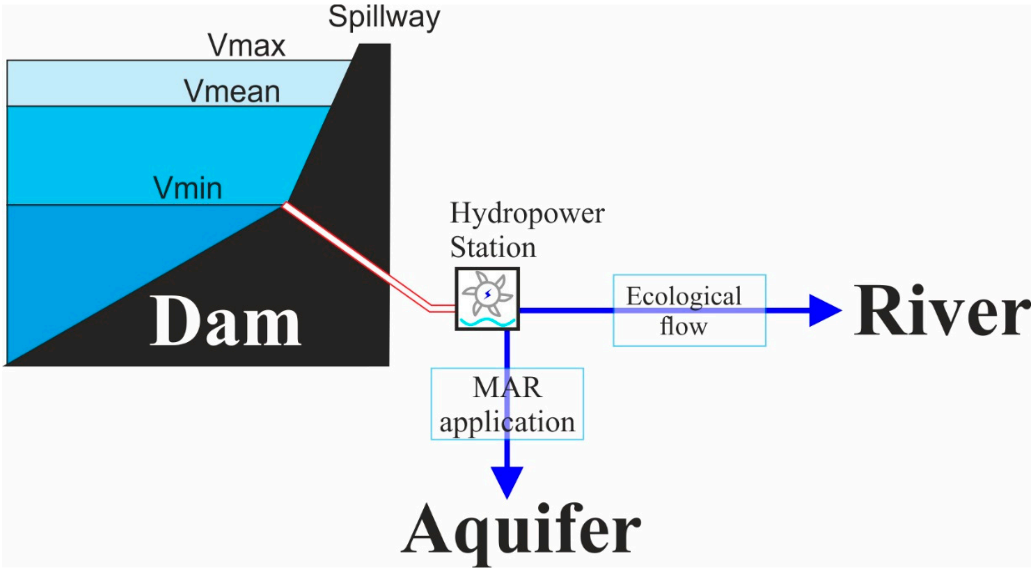

Figure 3. Conceptual model for optimizing reservoir.

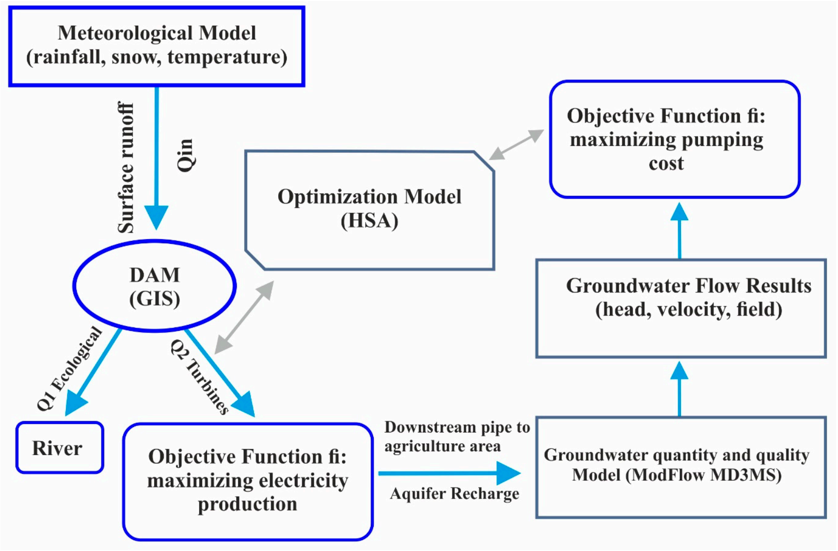

Figure 4. Flow chart of the optimization procedure.

The daily inflow and outflow of water in the reservoir constitute the hydrological data of the problem in the model, stored in csv files, and extracted from the model through a suitable Python script using the Pandas library.

For each dam, the level–supply curve has been calculated considering that the total volume of water in the reservoir has a semi-pyramidal shape, as shown in Figure 4. Considering that these dams are typically built at right angles to the flow of small streams, the provided geometric model closely approximates real-world conditions. It provides a straightforward and uncomplicated method for describing the effective reservoir volume, requiring only minimal geometric data.

The current volume at any specific moment, as determined by the continuity equation, results from the combined contributions of the cumulative input curve, the cumulative output–loss curve, and the cumulative consumption curve. There are two constraints applied to this volume. The first constraint pertains to a minimum volume, denoted as Vmin, representing a level below which water becomes unsuitable for energy generation. The second constraint relates to a maximum volume, designated as Vmax, corresponding to a level at which excess water would spill over the dam and flow into the receiving body. Equation (1) provides the expression for the current volume at time T:

$$V_{cur} = \int_0^T Q_{in}dt + \int_0^T Q_{out}dt + \int_0^T Q_{irrigation}dt + \int_0^T Q_{turbine}dt. \tag{1}$$

The geometric model of Figure 4 deals with cases where there is insufficient data with which to construct the level–supply curve. If a curve has been derived from previous studies, it can be used directly in the model. For the case of the simplified model, the relationship between current useful volume (Figure 5) and change in height is calculated via by Equation (2).

$$V_{cur} = \frac{1}{3}L * A_{base} = \frac{1}{3}L * \frac{DH_{cur}(B + (2A + B))}{2} \rightarrow V_{cur} = \frac{DH_{cur} * L * (A + B)}{3} \tag{2}$$

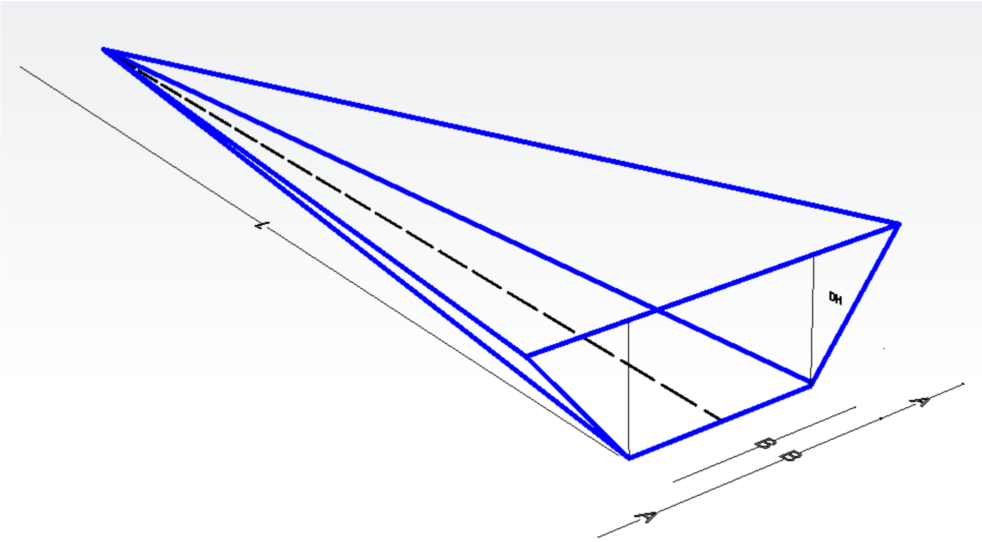

Figure 5. Volume Model of reservoir.

The model has two objective functions: energy production and groundwater recharge. The goal is to maximize the two objective functions, but it is not good practice to combine them into a summation function. The reason for this is the fact of the non-immediate response of the underground aquifer to recharge. Since the infiltration rates of water into the soil are low, there is a significant time lag between the surface drawdown of the aquifer and groundwater recharge. If it is assumed that all the water from the dam is immediately directed to the underground aquifer, then we will most likely flood the valley downstream of the dam. One way to overcome this obstacle is to consider energy production on a daily basis but the change in the groundwater level on a monthly basis; in other words, the average monthly water supply of the aquifer is calculated and reduced to daily proportions.

The objective of the optimization model is to determine the vector representing daily water allocations throughout the year for electricity generation and aquifer recharge. This equates to solving a problem with 365 × 2 variables. Constraints for this problem involve maintaining a reservoir volume at or above 10% of its maximum capacity, guaranteeing an ecological flow and imposing an upper limit on the reservoir volume to prevent excess water from spilling over. The model, in the form of equations, is presented in Table 2.

Table 2. The equations of the model.

Variables	Restrictions	Objective Function
$\vec{Q} = \begin{cases} x1_{turbine} & x1_{recharger} \\ x2_{turbine} & x2_{recharge} \\ x3_{turbine} & x3_{recharge} \\ \cdots & \cdots \\ \cdots & \cdots \\ x364_{turbine} & x364_{recharge} \\ x365_{turbine} & x365_{recharge} \end{cases}$	$V_{min} < V_{cur} < V_{max}$ $Qeco_{\mathrm{min}\,<}Qeco$	$F_1 = \sum_{0}^{365} \rho * g * Dh * Q_{turbine}$ $F2 = S_y \frac{\partial h}{\partial t}$ OR Equation (3)

Modflow 6 software was used to calculate the recharge of the underground aquifer. Since the optimization method requires multiple calls of the objective functiudflowe API call of modflow, flopy, in Python language was used. Alternatively, in the model, a second objective function was used instead of maximizing the recharge of the underground aquifer, i.e., the function of minimizing the pumping cost. These two parameters are directly related through Equation (3):

$$K = T_p \cdot C_{kWh} \cdot \frac{\rho \cdot g}{n_p} \cdot \sum_i^{NW} \frac{Q_i \cdot (s_i + \delta)}{10^3}, \tag{3}$$

where:

- T_p: the time duration of pumping in hours;
- C_{kWh}: the current price of kWh;
- ρ: the density of the pumped fluid in $\mathrm{Kg/m^3}$;
- g: the acceleration of gravity in $\mathrm{m/s^2}$;
- n_p: the efficiency rating of each pump;
- Q_i: the pumped flow in L/s;
- s_i: the water level drop at the side of the borehole in meters;
- δ: the distance of the resting level from the ground surface in meters.

6. Limitations of Dam Operation and Future Challenges

In line with climate change forecasts for the 21st century as projected by Global Climate Models (GCMs), Greece, situated within the Mediterranean region, falls within a climatic zone where there is an anticipated rise in temperatures and year-to-year fluctuations coupled with a diminishing pattern in precipitation. These climate alterations are poised to impact all sectors related to water resources, encompassing water supply, irrigation systems, sustainable energy sources, industrial manufacturing, and ecosystems.

The construction of reservoirs or modest dams is frequently advocated as the primary means of ameliorating the uneven spatial and temporal distribution of water in natural settings. This approach is put forward as a means by which to address both climate change challenges and water scarcity [86]. Reservoirs offer substantial advantages in multifaceted hydropower initiatives due to their capability to store surplus water during times of abundance and release it during periods of deficit. This enables energy generation, the fulfillment of irrigation and water supply needs, and flood control, all in alignment with demand patterns [77,87]. Nevertheless, any project related to water management must adhere to the guidelines set forth by the European Union Water Framework Directive (EU-WFD). This directive mandates that the management of water resources harmonize economic considerations with technical reliability to meet environmental and societal objectives [88]. Among the measures aimed at achieving the environmental goals of such projects, maintaining a minimum downstream discharge from both small and large dams that incorporate hydroelectric plants (HEP) is deemed crucial, ensuring that the ecosystem remains unaffected.

According to the International Commission on Large Dams' (ICOLD) definition, dams are categorized as large if their height exceeds 15 m, measured from the deepest foundation point, or if they create a reservoir with a capacity exceeding 3 × 106 cubic meters, with a height exceeding 5 m. Structures such as dikes or ponds meeting these criteria have also been included in the register [89]. Each dam has been assigned a unique registration number based on its date of commissioning.

A petite reservoir barrier is a construction established across a river, stream, or another aquatic body to amass water and fashion a reservoir or lake [90,91]. These smaller dams are tailored for localized requirements, contrasting with the larger counterparts designed chiefly for substantial water provision, emphasizing power generation and flood control.

These compact dams usually serve a multitude of roles and fulfill various demands [92–94]:

- To stockpile water for agricultural, industrial, or residential consumption. The reserved water can be employed for irrigation, livestock hydration, and other water-related purposes.
- To assist in mitigating soil erosion by diminishing the speed of water flow and allowing sediment to settle within the dam-created reservoir.
- To establish diminutive lakes or leisurely ponds, offering prospects for angling and other open-air pursuits.
- To form wetlands conducive to wildlife attraction and biodiversity sustenance.
- For energy production; while larger dams typically cater to extensive hydroelectric power generation, some smaller dams can also be equipped with turbines to produce electricity on a smaller scale.
- To furnish a degree of flood control by temporarily containing excess water during intense rainfall.

It is crucial to underscore that the characterization of a “small dam” can fluctuate based on individual country regulations. In certain regions, a small dam may pertain to structures of relatively modest dimensions, while elsewhere, the term might encompass a broader spectrum of sizes and functions [95,96]. Regardless of size, the construction and operation of any dam necessitate meticulous planning and supervision to ensure environmental sustainability, safety, and alignment with pertinent regulations.

These particular projects exhibit certain drawbacks, such as the following [97,98]:

- Environmental Consequences: Erecting small dams can have ecological ramifications, encompassing habitat degradation, alterations in river currents, and shifts in sediment transport, which can impact aquatic ecosystems and wildlife habitats. Additionally, dams can reduce groundwater recharge in lowlands aquifers.
- Sediment Accumulation: Small dams can trap sediment, resulting in sediment buildup within the reservoir. Over time, this can diminish storage capacity and influence downstream ecosystems.
- Maintenance and Oversight: Small dams mandate regular upkeep and oversight to guarantee their structural reliability and efficient functionality. Neglecting maintenance can escalate the risks of dam failure and associated hazards.

It is imperative to appraise the unique circumstances and prospective repercussions of small dam undertakings on an individualized basis. Environmental, social, and economic considerations, including community engagement and adherence to regulatory frameworks, should be incorporated to assure the sustainable development and governance of small dam initiatives.

While small dams can contribute to addressing certain facets of climate change, they cannot stand as an all-encompassing remedy on their own. Climate change is a multifaceted and intricate issue, necessitating an amalgamation of approaches and actions at varying levels to alleviate its consequences and adapt to shifting conditions. While small dams can present advantages in particular scenarios, they possess constraints and potential drawbacks that necessitate deliberation. A holistic strategy for combating climate change demands a confluence of tactics, such as transitioning to renewable energy sources, amplifying energy efficiency, adopting sustainable land use practices, safeguarding ecosystems, and bolstering community resilience [99]. Small dams should be scrupulously assessed and amalgamated into broader climate change strategies, acknowledging their advantages, restrictions, and plausible repercussions. Small dams can unquestionably exert a significant and affirmative influence in localized realms, conferring diverse advantages to communities, especially in regions characterized by scarce or unreliable water resources. Moreover, small dams can contribute to energy storage via a technique referred to as pumped storage hydro (PSH). Pumped storage hydropower involves stockpiling and generating electricity by utilizing two water reservoirs situated at differing elevations. Given that they fulfill certain geographical and hydrological criteria, they may be well-suited for pumped storage hydropower facilities.

As is presented within this study, in Greece, there are many dams without multi-scope operation. In many cases, the dams supply water during the summer (dry) period in the lowlands for domestic and agricultural use. Hence, the pumping rate of groundwater from the aquifer decreased. However, in some cases, dams serve only for flood protection, and the water remains within the reservoir (e.g., Anthemountas basin). In such cases, the recharge of lowlands aquifers decreased, and groundwater depletion occurred. Obviously, the hydrogeological conditions and, specifically, the interaction between groundwater and surface water should be quantified in the basin with respect to existing dams. The issue is also important in most countries of the Middle East and North Africa, as there is a negative balance between consumption and groundwater recharge. In many cases the recharge is less than 50% of the pumping water [100]. Many aquifers are transboundary aquifers, making their management problem more complex. IN the case of the United Arab Emirates, GIS have been developed which include maps with the recharge rates of groundwater reserves [101]. The effects of climate change are expected to affect underground aquifers through the increase in temperature and the phenomenon of evaporation and transpiration, but also through the strong change in rainfall, both spatially and quantitatively. According to climate models, an increased frequency of extreme events such as droughts and floods is expected. In addition, North African countries are likely to suffer disastrous consequences due to their geographical location, economic dependence on sectors directly related to the climate, lack of organized water resource plans, and insufficient political decisions [102].

The application of managed aquifer recharge is also a method of improving water quality, especially in coastal aquifers. MAR has proven to be an economically advantageous solution in relation to desalination [103], while various methods can be adopted in different hydrogeological environments. The application of MAR and the optimization of hydropower production constitute a challenge which requires the quantification of budget alternations between hydropower, energy, and water reserves. This aspect will be presented in a future application in selected dams in Greece. Hopefully, researchers could apply this approach in other sites in order to obtain a comparison in different environments. The suggested algorithm (HAS) is characterized by the simplicity of its implementation and its ability to avoid local extrema in a relatively fast convolution. This method cannot be compared with other meta-heuristic methods, as the theorem of "No free Lunch-NFL" applies to all of them, without exception [104]. Nevertheless, its application in several case studies might quantify the results of this approach.

7. Conclusions

The optimization of dam operation to produce hydropower and simultaneously reinforce groundwater reserves constitutes a challenge to blunting the impacts of the climate crisis. The proposed method presents a comprehensive approach to the multi-criteria optimization of small water reservoirs, taking into account energy production and groundwater enrichment. A simple and easily modifiable optimization model is presented, which can be applied to various dam cases if the appropriate geometric and physical data are available. The methodology introduced in this study represents a versatile computational framework that holds significant potential for a wide range of applications, either in its original form or with tailored adjustments. One notable area of application is the optimization of small-scale reservoirs, where the focus is on enhancing both electricity generation and the replenishment of underground aquifers. By integrating these two crucial objectives, this approach has the capacity to generate diverse sets of optimal solutions, essentially forming a spectrum of choices for policy-makers. In the context of small reservoirs, this computational framework can prove invaluable; it empowers decision-makers with a multitude of carefully crafted solutions to select from, taking into account the specific requirements, constraints, and priorities of the given situation. Whether the emphasis is on maximizing energy production, promoting sustainable groundwater recharge, or finding a balanced compromise between the two, this methodology provides a systematic and data-driven approach to inform decision-making.

Furthermore, the adaptability of this framework enables it to be applied in various geographical and environmental contexts, making it a valuable tool for addressing the complex challenges associated with managing small reservoirs. With the ability to explore trade-offs and optimize outcomes, it facilitates more informed and effective decision-making processes, ultimately contributing to the sustainable and efficient utilization of water resources in multi-faceted settings.

Within this study, an overview of algorithms and water quality indices for reservoirs and dam dynamics in Greece was obtained. The conclusions are be summarized below:

- The are more than 235 dams in Greece with the potential to use water for MAR application;
- The water quality of reservoirs is variable and should be periodically checked;
- The water quality index SRDD is used in the majority of case studies in the literature;
- The HSA algorithm is suggested as the most useful for hydropower generation and MAR application.

This study illustrates that the transformation of small dams for energy production and MAR application is feasible and that there are numerous tools with which one can achieve it. Nevertheless, hydrogeological monitoring and modeling are required in order to avoid failures.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15213852/s1, Table S1: Characteristics of dams in Greece; Table S2: Overview of algorithm application for dam operation.

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