



Special Issue Reprint

Water Supply System (WSS) Reliability, Safety and Risk Modelling & Assessment

Edited by
Katarzyna Pietrucha-Urbanik and Janusz Rak

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Guest Editors

Katarzyna Pietrucha-Urbanik

Janusz Rak



Basel • Beijing • Wuhan • Barcelona • Belgrade • Novi Sad • Cluj • Manchester

Guest Editors

Katarzyna Pietrucha-Urbanik
Department of Water Supply
and Sewerage Systems
Rzeszow University of
Technology
Rzeszow
Poland

Janusz Rak
Department of Water Supply
and Sewerage Systems
Rzeszow University of
Technology
Rzeszow
Poland

Editorial Office

MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

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About the Editors

Katarzyna Pietrucha-Urbanik

Katarzyna Pietrucha-Urbanik, DSc, PhD, Eng., is an Associate Professor at the Department of Water Supply and Sewerage Systems, Faculty of Civil, Environmental Engineering and Architecture, Rzeszow University of Technology (Poland). Her research focuses on reliability and safety of municipal systems, water supply networks, operational risk analysis, safety of water supply consumers, failure risk analysis and reliability-based risk assessment of water distribution infrastructure.

Janusz Rak

Janusz Rak, PhD, DSc, Eng., is a Professor at the Department of Water Supply and Sewerage Systems, Faculty of Civil, Environmental Engineering and Architecture, Rzeszow University of Technology (Poland). His research interests include critical infrastructure protection, reliability and safety of water supply systems, consumer safety, failure modelling, risk analysis and reliability-based risk assessment supporting the resilient operation of water utilities.

Preface

Reliable and safe water management is a fundamental requirement for public health, infrastructure security, and sustainable development. This Reprint gathers peer-reviewed research devoted to the reliability, safety, and risk assessment of water supply systems and related water infrastructure. The contributions address water supply and distribution networks, water demand and hygiene-related water use, water safety plans, failure and reliability assessment, optimal network design, water quality and contamination issues, wastewater treatment, urban drainage performance, flood risk mitigation, water losses, water scarcity, and the water-energy nexus. By combining methodological, experimental, modelling, and case-study approaches, this Reprint supports more resilient, safe and sustainable planning and operation of water systems under technical, environmental, and societal pressures.

Katarzyna Pietrucha-Urbanik and Janusz Rak

Guest Editors

Water, Resources, and Resilience: Insights from Diverse Environmental Studies

Katarzyna Pietrucha-Urbanik * and Janusz Rak

Department of Water Supply and Sewerage Systems, Faculty of Civil, Environmental Engineering and Architecture, Rzeszow University of Technology, Al. Powstancow Warszawy 6, 35-959 Rzeszow, Poland

* Correspondence: kpier@prz.edu.pl

1. Introduction

Water is our most precious resource, and its responsible management and utilization are paramount in the face of ever-growing environmental challenges. “Water, Resources, and Resilience: Insights from Diverse Environmental Studies” explores a diverse array of water-related topics, showcasing the vital role water plays in our lives and ecosystems. This work delves into water’s usage, challenges, and innovative solutions, drawing from a wide range of environmental studies. This work maintains an encompassing scope, addressing subjects as varied as the equitable allocation of water resources, the intricacies of soil substrates, the sustainable generation of energy, and the critical interplay between water and public health [1,2]. It encapsulates the essence of water, elucidating its fundamental contribution to life’s sustenance, as well as its pivotal role in supporting agricultural practices, industrial processes, and energy production [3–7]. The work, with astute foresight, not only recognizes the contemporary status of water resources but also casts a discerning glance at the looming challenges precipitated by surging global population, climate change, and pollution, all of which accentuate the global water crisis [8–12].

Furthermore, this collection places significant emphasis on the harnessing of advanced technologies and analytical tools, as these have emerged as indispensable instruments in refining our understanding, efficient management, and judicious utilization of water resources [13–15]. Computational modeling, data-driven analyses, and the adept use of geographic information systems are fundamental in several of the articles, facilitating precise assessments, predictive simulations, and the identification of emerging trends [16–19].

Our motivation for compiling this scientific work arises from the urgent need to address water-related concerns that impact global sustainability [20–22]. The growing water crisis, exacerbated by factors such as climate change, population growth, and pollution, has compelled us to gather insights from various environmental studies [23–33]. We aim to disseminate knowledge that can drive positive change and foster innovative solutions for the responsible and sustainable management of our water resources [34–42].

The Special Issue was intended for a broad audience, including researchers, academics, policymakers, environmentalists, and anyone interested in water-related issues. It serves as a valuable resource for those seeking a deeper understanding of the challenges and opportunities within the realm of water resources and environmental studies. By addressing a wide range of topics, we aim to engage and inform a diverse readership, enabling them to contribute to the global dialogue on water sustainability.

In this volume, each chapter explores critical facets of water and its multifaceted role in our environment.

2. Materials, Methods, and Results

As we delve into the pages of this Special Issue, we are met with a diverse collection of research articles that span a wide spectrum of topics within the realm of water, environment, and sustainability. The depth and breadth of the contributions showcased in this

volume demonstrate the unwavering commitment of the global research community to understanding and addressing critical challenges related to water resources, environmental conservation, and sustainable practices.

The paper: Use of Water and Hygiene Products: A COVID-19 Investigation in Indonesia [43] investigates COVID-19's impact on hygiene and water use in Indonesia using online and national surveys. It reveals increased adherence to hygiene practices, specifically handwashing, and following health guidelines. This resulted in higher water and hygiene product consumption, unaffected by socio-economic factors. Respondents' COVID-19 perception and compliance with health guidelines drove these changes, with older individuals favoring handwashing and younger ones preferring hand sanitizer. The study also notes stagnant access to safe drinking water but a rise in bottled water consumption, posing challenges for SDG 6 targets. It underscores the importance of addressing COVID-19 perception to promote better hygiene practices and expresses concerns about increased water use, domestic pollution, and wastewater management during and after the pandemic. These findings can guide policymakers, researchers, and practitioners in public health and water management to achieve SDG 6 goals during and beyond the pandemic.

The paper: The Vital Roles of Parent Material in Driving Soil Substrates and Heavy Metals Availability in Arid Alkaline Regions: A Case Study from Egypt [44] addresses the understudied influence of diverse parent materials in arid alkaline regions, focusing on four types: fluvio-marine, Nile alluvial, lacustrine, and aeolian deposits. The investigation assesses their impact on soil properties like clay content, bulk density, pH, and available phosphorus (AP). Statistical tests and meta-regression models are employed to analyze the data. Notably, alluvial deposits exhibit significantly higher soil organic carbon (SOC) and total nitrogen content compared to other deposits. Additionally, aeolian deposits contain more iron (Fe), while alluvial deposits have elevated levels of zinc (Zn), manganese (Mn), and copper (Cu). Soil parent material is a key factor affecting Fe content, while bulk density influences Zn and Mn levels, and SOC drives Cu content. This research contributes valuable insights into understanding soil substrate dynamics and heavy metal availability, considering variables such as parent materials, pH, bulk density, and clay content.

The research entitled: Hybrid Optimization Algorithms of Firefly with GA and PSO for the Optimal Design of Water Distribution Networks [45] delves into innovative optimization techniques to enhance the design of water distribution networks, by combining Particle Swarm Optimization (FAPSO) and the Firefly Algorithm with Genetic Algorithm (FAGA), which has been introduced to enhance the efficiency of the conventional Firefly Algorithm for designing cost-effective water distribution networks. These models underwent rigorous testing and were applied to both established benchmark networks found in the literature and a real-world case study in El-Mostakbal City, Ismailia, Egypt. The performance assessment of these algorithms included evaluating cost-related metrics, function evaluations, computational time for 1000 evaluations, and a success rate determined using fuzzy logic for solutions slightly exceeding the known optimal solution (by approximately 1.0% and 2.0%). The results demonstrated that the FAGA model surpasses the standard Firefly and FAPSO models in terms of effectively exploring the search space, exploiting promising areas, and converging toward optimal solutions. This indicates FAGA's potential as a robust optimization technique for water distribution network management.

Regulatory measures, such as submerged vanes, are essential for mitigating and preventing environmental damage caused by increased river flooding. Elevated flow velocities can lead to erosive scouring on the outer riverbank, resulting in adverse changes to the riverbed. This paper: Experimental and Numerical Study on Flow Control Using 3-Array Submerged Vane in Laboratory Channel Bend [46] focused on investigating the impact of flow velocities in proximity to the outer bank through experimental testing using a 3-array submerged vane structure in an open channel setup. The results from the experimental vanes were verified and compared to Computational Fluid Dynamics (CFD) outcomes using a standard-based $k-\varepsilon$ turbulence model. The CFD model closely approximated the real experimental results. In the outer meander, the three-array submerged vane with a

three-vane structure was found to reduce flow velocity by 16–27% in the vane's downstream area, with flow velocity decreasing by 14–21% along the depth. This study recommends the implementation of submerged vane structures as an effective approach to decrease flow velocities and guide water flows.

The concept of floating photovoltaic plants presents an innovative approach to address water evaporation issues while generating clean energy. A case study from Lake Nasser in Egypt illustrates the potential of this technology in water-stressed regions, as presented in Floating Photovoltaic Plants as an Effective Option to Reduce Water Evaporation in Water-Stressed Regions and Produce Electricity: A Case Study of Lake Nasser, Egypt [47]. This research aims to address two critical issues concerning water and energy while conserving these resources. The study proposes the use of floating photovoltaic (FPV) panels with partial coverage on Lake Nasser. Results reveal that partially covering Lake Nasser with FPV panels offers an effective solution for preserving Egypt's water resources, which are strained due to water scarcity. This approach significantly reduces water evaporation from Lake Nasser by 61.71% (equivalent to 9,074,081,000 m³/year) and generates an annual electricity output of 467.99 TWh/year when 50% of the lake's area is equipped with FPV panels.

A green approach to wastewater treatment is explored in the paper: Simultaneous Removal of Metal Ions from Wastewater by a Greener Approach [48]. The research emphasizes the significance of sustainable and environmentally friendly methods for metal ion removal from contaminated water sources. Results indicated that higher initial metal ion concentrations led to increased adsorption capacity, but decreased the removal efficiency of *S. cerevisiae* yeast cells. The best results were achieved at specific conditions: pH 5.0, 2.0 g *S. cerevisiae*/L, 25 °C, and a 25-min contact time. The maximum adsorption capacities (q_{max}) for Pb(II), Cd(II), and Ni(II) ions were 65, 90, and 51 mg/g, respectively, as per the Langmuir model. The biosorption reactions for metal ions were spontaneous and followed the pseudo-second-order model. Mechanisms of metal ion removal were elucidated using XRD, FTIR, BET, and TEM analyses. Additionally, EDTA and citric acid proved effective in desorbing adsorbed ions. Storage experiments revealed that immobilized *S. cerevisiae* remained stable for up to 8 months, surpassing the raw yeast instability.

The World Health Organization (WHO) has endorsed the use of Water Safety Plans (WSPs) as a highly effective approach for enhancing water safety management since 2004. While the implementation of WSPs is gaining global traction, there remains a lack of a standardized methodology for conducting WSP verification. The paper: Long-Term Assessment of a Water Safety Plan (WSP) in Salta, Argentina [49] presents a comprehensive assessment of a specific WSP five years after its initial adoption. The study scrutinizes the risk assessment methodology utilized by a water utility in Salta, Argentina, and appraises the execution of control measures. To objectively gauge the WSP's effectiveness, water quality parameters and customer complaints are analyzed over time. The findings reveal that while certain control measures were put in place and risk values decreased, persistent issues in Salta's water supply, like customer complaints and high turbidity levels during the rainy season, remained unresolved. The article also emphasizes the role of rigorous scientific evaluations and the significance of legislative and regulatory bodies in WSP implementation.

Flash floods pose severe risks in arid regions. This case study entitled: Evaluation and Mitigation of Flash Flood Risks in Arid Regions: A Case Study of Wadi Sudr in Egypt [50] explores methods for evaluating and mitigating these risks, contributing to improved disaster management strategies. The research employs an integrated approach, combining the Geographic Information System (GIS) and the Watershed Modeling System (WMS) with HEC-HMS to analyze and visualize flood events in the area. Various geomorphological parameters of the watershed are determined, encompassing linear, areal, and relief characteristics. GIS is utilized to analyze satellite images, identify valley attributes, and delineate stream orders. WMS is employed to estimate rainstorms, basin features, and rainfall thresholds for flooding. HEC-HMS is used for hydrological modeling and flood

estimation. The analysis of morphometric and hydraulic parameters reveals that Wadi Sudr encompasses 4029 streams of the seventh order, covering an area of 547.45 km². The study identifies two potential dam locations for flood protection, with a comparison indicating that the first location is more suitable based on several criteria, including storage capacity, water depth, valley shape, and construction cost efficiency. The study uses the weighted linear combination (WLC) method to confirm the suitability of the first location. The proposed dam is expected to efficiently mitigate flood risks and enable water utilization for various purposes. This methodology holds potential for application in other areas facing flash flood hazards.

Urban rainstorm drainage systems play a vital role in managing water in urban environments. The research entitled *Effect of Changing the Shape and Size of Inlet Area of Grates on the Hydraulic Efficiency of Urban Rainstorm Drainage Systems* [51] examines the impact of changes to the inlet area of grates, enhancing our understanding of hydraulic efficiency in drainage systems. The study explores five distinct grate shapes and three relative inlet areas (26%, 51%, and 64%). The results indicate that the most efficient grate shape is type 4, with an 8.7% reduction in discharge efficiency. Altering the inlet area size from 26% to 64% significantly impacts the systems' efficiency, decreasing it by 4%. The study also utilizes dimensional analysis and multiple regression analysis to develop an empirical equation for calculating drainage system efficiency. The findings offer insights for decision-makers to optimize maintenance scheduling, potentially saving costs. The empirical equation aids in monitoring grate blockage and its impact on efficiency. This study's outcomes can inform future road drainage system construction, enhancing their effectiveness and reducing urban flood risks.

The final contribution to this Special Issue entitled *Advances in Assessing the Reliability of Water Distribution Networks: A Bibliometric Analysis and Scoping* [52] offers a comprehensive bibliometric analysis and scoping review, illuminating the latest advances in assessing the reliability of water distribution networks. Water Distribution Network (WDN) reliability is a crucial subject that has garnered increased attention over the past decade, with a growing body of research exploring various aspects of this field [53]. This study conducts a bibliometric analysis and scoping review to assess the progress and identify research gaps in WDN reliability. Three primary research themes are discerned: WDN optimization, reliability assessment, and the consideration of greenhouse gas (GHG) emissions and energy costs in WDN expansion. Reliability surrogate measures (RSMs) emerged as a heavily researched topic. Meanwhile, evaluating the performance of various RSMs and incorporating energy and cost considerations into WDN design and expansion are identified as emerging research trends in WDN reliability.

3. Conclusions and Perspectives

In conclusion, 'Water, Resources, and Resilience: Insights from Diverse Environmental Studies' brings together a rich tapestry of research contributions that collectively emphasize the paramount importance of water management and sustainability. As our global community faces escalating water challenges driven by climate change, population growth, and pollution, the need for innovative solutions and informed decision-making becomes increasingly urgent. This collection of studies provides a multifaceted exploration of water-related topics, ranging from the impacts of the COVID-19 pandemic on hygiene practices in Indonesia to the intricate geomorphological parameters affecting soil substrates in arid regions. The insights derived from these studies offer a mosaic of knowledge and strategies to address the complex and evolving water issues of our time.

One overarching theme that emerges is the necessity for interdisciplinary collaboration. Water resources touch upon a multitude of aspects, encompassing public health, environmental conservation, energy production, and infrastructure engineering. These studies reflect the interconnected nature of water, emphasizing the need for cooperative efforts among researchers, policymakers, and practitioners to develop holistic solutions [54–60].

The application of advanced technologies and analytical tools is a prevailing trend, aiding researchers in their quest to better understand, manage, and harness water resources. Computational modeling, data analysis, and geographic information systems have been instrumental in several of the studies, enabling precise assessments and simulations. In this regard, the incorporation of artificial intelligence (AI) presents an exciting avenue for future research. AI, with its ability to process vast datasets and derive meaningful insights, can enhance the precision and efficiency of water-related studies. Machine learning algorithms, for instance, can aid in predictive modeling for water quality, demand forecasting, and flood risk assessment [61].

Moreover, the findings underscore the importance of adaptable and environmentally friendly approaches. The utilization of submerged vanes to control river flows, the deployment of floating photovoltaic panels to mitigate water evaporation, and the exploration of greener methods for wastewater treatment exemplify sustainable practices that can serve as blueprints for the future. These sustainable strategies not only conserve precious resources but also align with global goals for mitigating climate change and protecting ecosystems [62].

The focus on water safety and the assessment of water distribution networks highlights the significance of clean and reliable water supplies for public health and urban resilience. As urban areas continue to expand, addressing the challenges of urban rainstorm drainage systems, with a spotlight on the efficiency of grates, is a vital concern. These studies offer valuable insights for urban planners and engineers striving to ensure cities can effectively manage rainfall and minimize flooding.

Finally, this collection of studies takes a significant step toward expanding our understanding of WDN reliability. In a world where water scarcity is a looming crisis, the assessment and optimization of water distribution networks play a pivotal role. The bibliography analysis and scoping review illuminate the research landscape and pave the way for future investigations. AI, with its data-driven capabilities, can revolutionize this field by optimizing WDN designs, predicting maintenance needs, and enhancing reliability through smart sensors and real-time monitoring [63].

In perspective, this comprehensive body of research encourages us to pursue sustainable water management practices, embrace technological innovations, and engage in interdisciplinary collaboration. AI, coupled with big data analytics, can play a pivotal role in these pursuits, offering the potential to revolutionize water resource management. By leveraging AI's capabilities, researchers can develop predictive models, optimize resource allocation, and enhance decision-making processes. AI-driven monitoring systems can provide real-time insights into water quality, usage patterns, and network vulnerabilities, thereby promoting resilience and sustainability [64–73].

As we stand at the threshold of a future where water scarcity threatens communities and ecosystems, the insights and methodologies presented in this collection provide a ray of hope. They serve as a reminder that, equipped with knowledge, innovation, and cooperation, we possess the means to address the water challenges of our time and safeguard this invaluable resource for future generations. This work exemplifies the collective commitment of the global research community to advance water resource management and contribute to the construction of a more sustainable and resilient world.

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Acknowledgments: Each of these articles encapsulates the dedication of researchers worldwide to advancing knowledge and promoting sustainable practices in the fields of water resources, environmental management, and infrastructure design. As editors of this Special Issue, we are honored to present this collection of research articles to our readers, and we trust that the insights provided by these studies will contribute to ongoing discussions and actions aimed at addressing some of the most pressing challenges in the areas of water, environment, and sustainability. We extend our sincere appreciation to the authors, reviewers, and all those who have contributed to the realization of this Special Issue. Your collective efforts have been instrumental in bringing these research findings to the forefront. We look forward to continued collaboration and the pursuit of innovative solutions to global challenges in the years to come.

Conflicts of Interest: The authors declare no conflict of interest.

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Advances in Assessing the Reliability of Water Distribution Networks: A Bibliometric Analysis and Scoping Review

Swati Sirsant¹, Mohamed A. Hamouda^{2,*} and Mostafa F. Shaaban³

¹ Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad 382481, Gujarat, India

² Department of Civil and Environmental Engineering, Faculty of Engineering, United Arab Emirates University, Al Ain P.O. Box 15551, United Arab Emirates

³ Department of Electrical Engineering, Faculty of Engineering, American University of Sharjah, Sharjah P.O. Box 2666, United Arab Emirates

* Correspondence: m.hamouda@uaeu.ac.ae

Abstract: The reliability of Water Distribution Networks (WDNs) is a critical topic that has been explored by many researchers over the last few decades. Nevertheless, this research domain has gained momentum in the last decade. WDN reliability was addressed in the literature using different approaches and techniques. This study presents a bibliometric analysis and scoping review of the progress and gaps in research on WDN reliability. The analysis was performed on a total of 347 articles from 2000 to 2022, which were retrieved from the SCOPUS database. The bibliometric analysis identified trends and gaps by focusing on articles output, citation network of articles, co-authorship and collaboration analysis, co-citation, and clustering analysis. In addition, coupling keywords analysis with thematic maps analysis helped identify basic, niche, emerging, and declining research themes in the field of WDN reliability. Three major research themes were found: WDN optimization, reliability assessment, and consideration of GHG emissions and energy-cost for WDN expansion. Reliability surrogate measures (RSMs) were found to be one of the most widely researched topics in this field. Performance assessment of various RSMs, as well as the consideration of energy and cost for WDN design and expansion stood out as the emerging trends for future research in the field of WDN reliability.

Keywords: reliability; water distribution networks; bibliometric analysis

1. Introduction

Water Distribution Networks (WDNs) are subject to hydraulic and mechanical failures. The performance assessment of WDNs, considering both failure and operating conditions, falls under the general term of WDN reliability [1]. Various techniques exist in the literature to conduct a representative reliability assessment of WDNs, including: the minimum cut set method [2], Monte Carlo simulation (MCS) [3], node availability [4], node-reliability factor, volume-reliability factor, and network reliability factor [5], etc. Most of these techniques require prohibitively long computational time and power when applied to complex real-world networks. For example, computational times of 19.72, 43.95, and 90.5 h were reported a hydraulic reliability-based design using the MCS method of the standard WDNs: Two loop, GoYang, and Fossolo, respectively [6]. Similarly, for a mechanical reliability-based design using the minimum cut set method, computational times of 1.211, 2.825, and 9.083 h were reported for Two loops, GoYang and Fossolo WDNs, respectively [6]. To overcome this issue, several studies presented reliability surrogate measures (RSMs), such as entropy [7], resiliency [8], network resilience [9], modified resilience index [10], etc., to reduce the computational time and reach a near-optimal solution, even when considering multiple objectives.

Several studies highlighted the importance of consideration of reliability in the design of WDNs such as [11–13]. Many studies formulated the reliability-based design problem as a single objective optimization by minimizing cost while setting a constraint on reliability [12,14,15]. Several other studies used the multi-objective optimization approach [16–19]. Studies have also highlighted the importance of the selected optimization tool in solving the reliability-based design problem of WDNs; some of the most commonly applied mathematical programming optimization tools include linear programming (LP) [20,21], non-linear programming (NLP) [22], mixed integer linear programming (MILP) [23], and mixed integer non-linear programming (MINLP) [24–26]. Subsequently, several Evolutionary Algorithms (EAs) were employed to solve the problem of the reliability-based single and multi-objective design of WDNs, such as Genetic Algorithm (GA) [27–29], Particle Swarm Optimization (PSO) [30–32], Ant Colony Optimization (ACO) [16,33], and Differential Evolution (DE) [12,15] for single objective optimization and Multi-Objective GA (MOGA) [34–36], Multi-Objective DE (MODE) [13,37,38] and Multi-Objective PSO [39–41] for multi-objective optimization. In addition, several other modeling factors were incorporated into studies of WDN reliability, such as the prediction of failure probability of pipes [42–44], the allocation of isolation valves [45–47], leak detection and quantification [48–51], etc. Thus, several approaches were proposed in the literature for the reliability-based design of WDNs with varying considerations of the factors influencing WDN reliability.

Some bibliometric reviews concerned with Water Distribution Systems (WDSs) [52] and the resilience of WDNs [53] recently appeared in the literature. A bibliometric analysis quantitatively assesses trends in a specific research field by conducting statistical and metadata analysis of the typical attributes of articles published in a particular domain, including the title, authors, keywords, date of publication, number of citations, etc. [52,53]. It also helps discover the subtle differences in the scientific evolution of a specific domain. More specifically, it can be effectively used for quantifying the research output from different authors, the collaboration between the authors, countries, universities, and the impact of different authors and articles on the advancement of a specific field [54]. The previous analysis focused on WDSs in general, considering all problems such as optimal design, risk assessment, etc. [52], whereas another bibliometric review focused on the resilience assessment of WDNs [53]. Resilience is, however, a subset of reliability assessment for WDNs. Thus, a broader bibliometric analysis and scoping review is needed to provide a better direction on the use of different optimization tools for reliability-based design, expansion, and maintenance planning of WDNs. Therefore, this study, for the first time, presents a bibliometric analysis and scoping review of reliability assessment tools for managing and designing WDNs. The primary research questions answered by the analysis pertain to the identification of the dominant research themes in the domain, their extent of exploration, the nature of collaboration, key concepts, tools, and applications, as well as research gaps, and recommendations for future research on WDN reliability assessment. Thus, the study can be useful to researchers in the field for scoping future research and identifying collaboration opportunities.

2. Background

Consideration of reliability dates to Goulter and Morgan (1985) [55], who considered redundancy in the pipe network as a measure to ensure reliability in the network. Some studies focused on the consumer's perspective of reliability by assigning a damage function to each consumer, that defines the damages caused when the demands are not met [56]. Other studies presented a methodology for reducing the impacts of failures in WDNs by minimizing the negative effects on consumers and operational costs [57]. A recent study focused on the consumers' lack of water supply by identifying the longest suspension time [58]. In addition, inherent deficiencies in WDSs, such as inadequate disinfection, low pressure, intermittent operations, leakages, and corrosion, can lead to decreased quantity as well as the quality of water reaching the consumers [59]. Fluctuating pressures in the WDNs have also led to the development of advanced automated tools operating

the amount of inflow to the system, including pumps and valves [60]. However, most articles have focused on quantifying the hydraulic and mechanical reliability of WDNs, as these can be accurately modeled. Bao and Mays [1] clearly distinguished between the hydraulic and mechanical reliabilities of WDNs. They defined hydraulic reliability as water demand satisfaction considering uncertainty in parameters, such as demand and pipe roughness coefficient, while mechanical reliability was defined as demand satisfaction considering the failure of one or more pipes. Goulter [61] presented the multi-objective optimization approach for the reliability-based design of WDNs based on the constraint method. Su et al. [2] presented the minimum cut set approach for mechanical reliability estimation of WDNs, which is one of the most widely used approaches. Jacobs and Goulter [62] presented the graph theory-based approach for the reliability analysis of WDNs. Bhawe and Gupta [63] represented uncertainty in decision variables by fuzzifying the variables. Shibu and Reddy [64] presented a fuzzy probabilistic approach to transform uncertainty in variables into fuzzy random variables.

Reliability assessment tools can be classified into two major classes: hydraulic and mechanical. Hydraulic reliability can be estimated using techniques such as MCS, First Order Second Moment (FOSM), node-reliability, volume-reliability, and network reliability factors. The most used techniques for mechanical reliability estimation include the minimum cut set approach and the simple probabilistic approach. The classification of the reliability assessment approaches is presented in Figure 1.

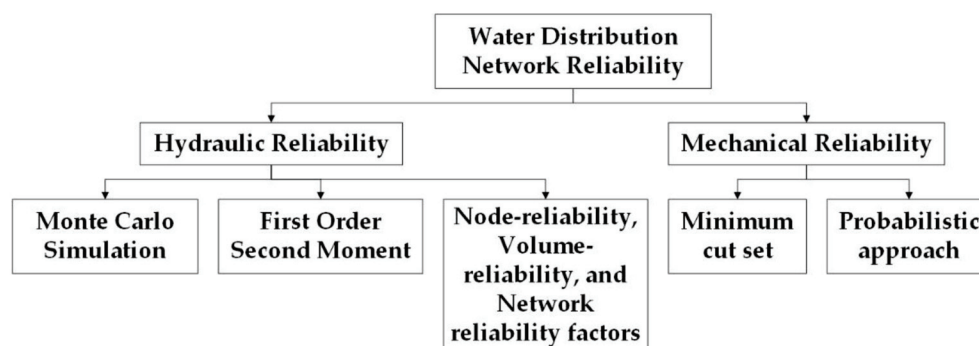


Figure 1. Classification of reliability assessment approaches.

The following is a summary of the typical application of these tools in the reliability assessment of WDNs:

- The MCS method involves generating random values for uncertain variables, such as nodal demands and/or pipe roughness coefficients. The random variables are usually modeled by assuming that they follow a certain probability distribution with a deterministic mean and a certain percentage of the mean as the standard deviation. The network is then analyzed for each of these random samples of uncertain variables. The reliability is then estimated as the ratio of the number of times the system performed satisfactorily to the total number of samples. The system is in failure condition if at least one of the nodes has any deficit in supply. The advantage of this approach is that it is easy to implement, while the major disadvantage is that it requires a substantial amount of random sample generation, making it a very time-consuming process.
- The FOSM includes the estimation of the covariance matrix of output parameter(s) as a function of the variance of the model input parameters. In addition, the gradient of the model output with respect to the model input parameters is calculated. The WDN needs to be evaluated for $K + 1$ scenarios (K being the number of input parameters and one base scenario, where the parameters are assumed to be certain). The main advantage of the FOSM method is that it does not require the substantial number of simulations needed in the MCS method. The drawback of the method is that it becomes inefficient in cases of large variations in the random variables, since the effect

- of non-linearity in the model becomes dominant, thereby deteriorating the accuracy of the model.
- Node reliability factor is defined as the ratio of available outflow to desired outflow volume at a node. Volume reliability factor is defined as the ratio of the total outflow volume to desired outflow volume for the entire network, considering all the states during the analysis period. Network reliability factor is calculated by multiplying the time factor and node factor with the volume reliability factor. The advantage of considering these factors is that they provide a more accurate picture of the reliability values when compared to the normal approach followed in the MCS method. The drawback of this method is that it requires significant computational time, as it employs the MCS approach.
 - Minimum cut set is defined as the minimum number of components that, upon collectively failing, causes a system failure. However, if any of the components is in a working state, the system failure would not occur. Thus, for a branched network, the failure of a single component can lead to the failure of the entire network; in a looped network, simultaneous failure of two or more components might be needed to cause system failure. This implies that the size of the cut set would be different for different networks. The reliability of the WDN is estimated as the demand satisfaction considering failure of each of these minimum cut sets.
 - The probabilistic approach considers that the failure probability of each pipe is the same and thus estimates reliability as the demand satisfaction under the simulated failure of each pipe at a time and aggregate for all failure situations. Different tools exist to determine the failure scenarios, such as reliability block diagrams [65], failure tree analysis [66], etc.

3. Methodology

The methodology of the analysis conducted in this study involved three steps: (1) data extraction; (2) bibliometric analysis; and (3) content analysis. The framework of the methodology is presented in Figure 2. The research questions addressed in the study are presented first, followed by the details of each of these steps.

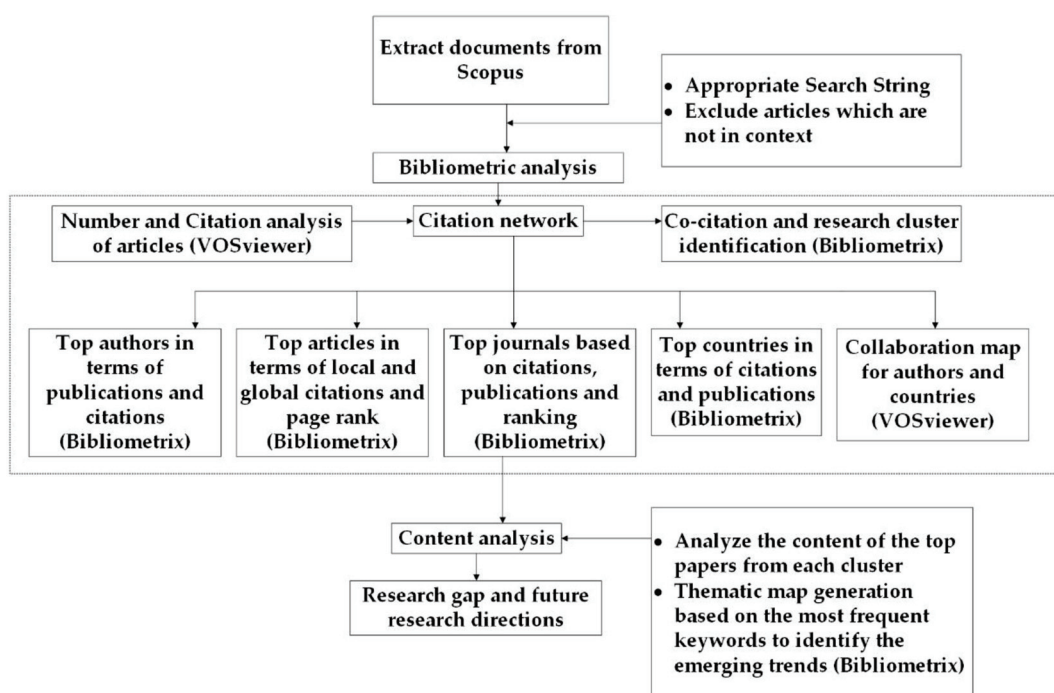


Figure 2. Overall methodology.

3.1. Research Questions

This bibliometric analysis will address the following research questions (RQs):

- What trends and patterns can be detected by analyzing articles on WDN reliability in terms of:
 - a. The number of relevant publications and citations.
 - b. The countries that contributed the most to the knowledge base.
 - c. The top journals that have published the most cited articles on the topic.
 - d. The top articles in the literature that have the greatest impact in terms of citation as well as page rank analysis.
 - e. The top authors in the literature that have the greatest impact in terms of number of publications and citation.
- What is the nature of collaboration in the field of WDN reliability as evidenced by co-authored publications?
- What are the key concepts, tools, and applications that have been explored in the field of WDN reliability and how they are related?

In addition, the article will discuss research gaps, and make recommendations for future research on WDN reliability assessment and related applications.

3.2. Data Extraction

Data extraction included the retrieval of documents related to WDN reliability from different literature databases. In the present study, “SCOPUS” was used as the search database due to its wider range of journal coverage compared to databases, such as “Web of Science”, “ERIC”, or “IEEE Xplore”. The search focused only on peer reviewed journal articles. The search found 808 documents when (TITLE (water AND distribution AND network *) OR TITLE (water AND supply AND network *) OR TITLE (water AND distribution AND system *) AND TITLE-ABS-KEY (reliability)) were considered. Upon limiting the search to document type “article”, language “English”, and publication year “2000–2022”, 347 articles were selected for detailed analysis.

3.3. Bibliometric Analysis

Bibliometric analysis involves quantitative and statistical analysis of the literature [59]. In the present study, the analysis was carried out by determining the following aspects:

- (1) The number of documents and citations in a defined period.
- (2) The top authors publishing articles in the field of WDN reliability by number of publications and citations and their collaborations.
- (3) Top articles by the number of citations.
- (4) The top countries producing articles in the field of WDN reliability and their collaborations.

The analysis was performed using two open-source software packages, VOSviewer V.1.6.18 and Bibliometrix V.4.0.1, as suggested by past studies [52,53]. VOSviewer was employed to generate the collaboration maps for different authors and countries, as well as the citation network of authors. Bibliometrix was used to present statistical data regarding the number of publications and citations for different authors, articles, countries, and journals [67]. To determine the ranking of the articles in the co-citation network, page rank was used as a measure. Page rank is a measure of how often and where the article has been cited [53]; it implies that, if the article has been authored by highly cited authors and cited by highly cited articles, the page rank for that article would be high. Page rank for journal citation network was estimated using the following equation [68,69]:

$$PR_n(J) = \frac{\pi^{(k)T}}{p_{n-1} + p_{n-2}} \quad (1)$$

where $\pi^{(k)T}$ = Page rank vector at the k th iteration, p_{n-1} and p_{n-2} are the number of papers published in journal J in the years $n - 1$ and $n - 2$, n being the current year, and $\pi^{(k)T}$ is updated using the following equation

$$\pi^{(k+1)T} = \pi^{(k)T}(\alpha H + (\alpha a + (1 - \alpha)e)1/ne^T) \quad (2)$$

H = very sparse, row substochastic hyperlink matrix, α = scaling parameter between 0 and 1, a = binary dangling node, and e^T = row vector of all 1 s.

3.4. Content Analysis

The content analysis consisted of two parts:

Cluster analysis: The co-citation network of the authors in the field of WDN reliability was generated to formulate clusters for different authors based on their common citations. The top articles by global citations from each cluster were then selected to identify the common themes of the various journals. Thereafter, the clusters were generated for author keywords to determine the focus areas of different articles based on the commonly used keywords in them.

Thematic map generation: Thematic maps were generated based on the keywords for the various articles to determine the basic themes explored in various articles, the most widely explored themes, niche themes, and emerging themes. A theme is decided based on the common keywords used by a group of articles. Density and centrality were used to measure the development and influence of a particular theme. Density measures the strength of internal ties among all the keywords within a theme and so is a measure of the development of that theme. Centrality represents the extent of connection to other themes and can be used to measure the influence of the theme in the research field. The following equations were used to calculate the centrality and density of a theme [68]:

$$c = 10 \times \sum e_{hk} \quad (3)$$

e_{hk} is the count for collective occurrence of keywords h and k belonging to different themes.

$$d = 100 \times \sum e_{ij}/w \quad (4)$$

e_{ij} is the count for collective occurrence of keywords i and j belonging to the same theme and w is the total keyword count for the theme.

Conclusions were drawn in terms of the niche themes that require more exploration, emerging themes, and future research directions.

4. Results

4.1. Trend in Articles Output

The trend in the number of publications and citations with respect to time is presented in Figure 3. The number of publications has increased gradually over the years, with the highest number of publications in 2020 (39 articles). There was a slight decline in 2021. The number of citations, however, was remarkably high in 2000, with gradual decline over subsequent years with a sudden spike in 2005. The highest number of citations was in 2014 (939 citations). The number of citations, however, declined again over subsequent years. The figure shows that the number of citations has been increasing and decreasing over this period, despite an increasing trend in the number of publications in this field. This confirms findings from a recent literature review [70] that showed an increasing trend in the number of publications in the field of WDN optimization. This is also in agreement with findings from a similar analysis considering publications on the resilience assessment of WDNs [53]. This depicts the growing interest in the field of WDN reliability.

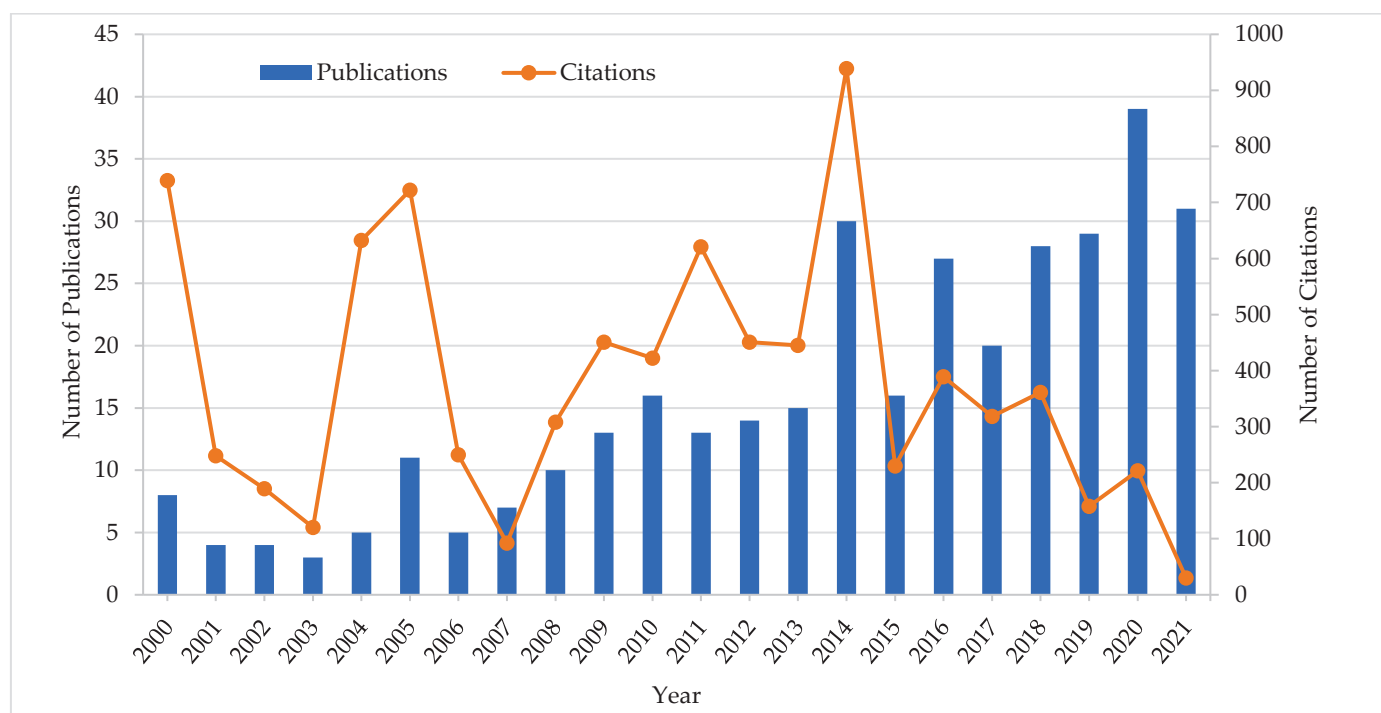


Figure 3. Number of articles and number of citations for articles published on the topic of reliability of WDN.

4.2. Citation Analysis of Articles

The contribution and impact of articles is depicted by citation analysis. Figure 4 shows the citation network of different articles with a minimum of twenty citations. This limit was selected to obtain a clear citation network map with readable fonts. The size of the node depicts the number of citations, while the links between the various nodes depict the collaboration between them. The distance between the nodes depicts the association between any two nodes in terms of co-citation. Three clusters are identified in Figure 4. Cluster 1 groups articles focusing on reliability/resilience assessment of WDNs. Cluster 2 groups articles focusing on reliability-based design of WDNs, while cluster 3 focuses on the optimal design of WDNs considering aspects of entropy, resiliency, and reliability.

The ten articles with the highest number of citations are presented in Table 1. The article [8], published in *Urban Water Journal*, is the most cited document. The probable reason for this is that the article introduced the resilience index as a surrogate for WDN reliability; this index is one of the most widely used RSMs. The ratio of local to global citations is 17.60%, implying that a significant fraction of the total citations fall in the field of WDN reliability. The Normalized Local Citations (NLC) and Normalized Global Citations (NGC) are calculated as the ratio of the actual (local/global) citations to the average number of citations for documents citing the article with the same year of publication [70]. NLC and NGC for [8] is 5.39 and 5.60, respectively, implying that it has around five times more citations when compared to similar articles published in the same year. The second highest cited article is [9], published in *Journal of Water Resources Planning and Management (JWRPM)*. The high number of citations may be credited to the fact that the paper introduced network resilience, another widely used RSM. The NLC and NGC values are 3.37 and 3.42, respectively, which shows a higher citation score (around three times) when compared to similar articles. The third highest number of citations is obtained for [71], published in *Engineering Optimization*, as it employs resilience in their study for multi-objective design of WDNs. The NLC and NGC values are also more than 1, implying it has been cited a greater number of times on average when compared to similar articles published in that

year. This shows that the use of RSMs, such as resilience and network resilience, has gained a wide popularity in last 22 years.

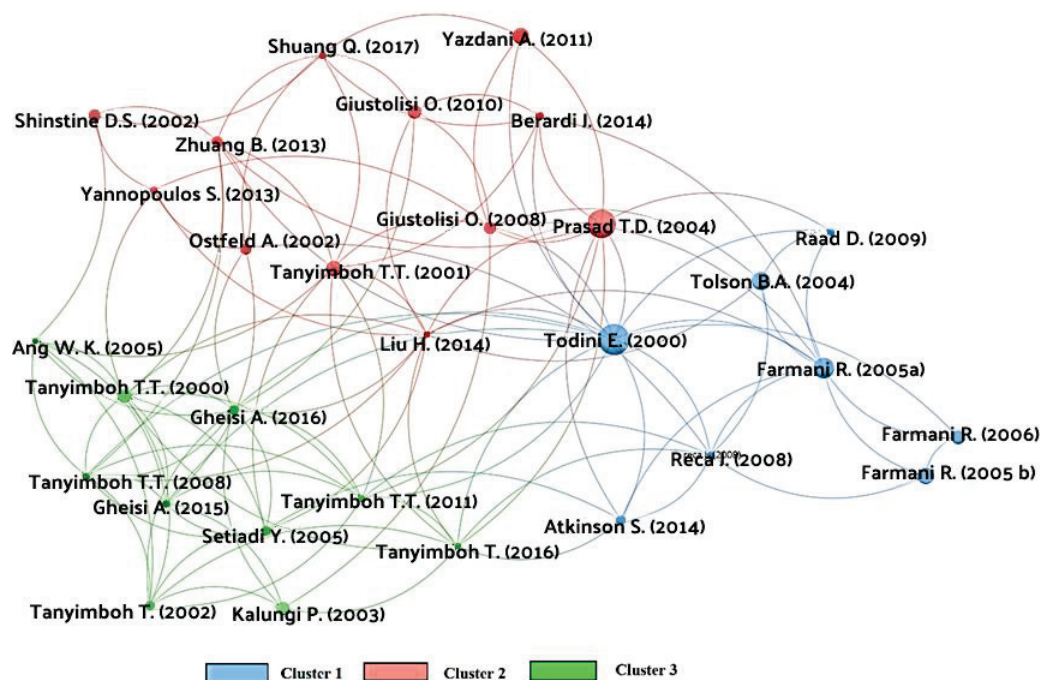


Figure 4. Citation network of articles: the node size represents citation number; the link between different nodes represent the collaboration between them; the distance between nodes represents the association between them in terms of co-citation.

Table 1. Top ten articles with highest number of citations.

Author, Journal	LC	GC	LC/GC (%)	NLC	NGC
Todini (2000) [8], Urban Water Journal	91	517	17.60	5.39	5.60
Prasad and Park (2004) [9], Journal of Water Resources Planning and Management	70	432	16.20	3.37	3.42
Tanyimboh and Templeman (2000) [71], Engineering Optimization	38	97	39.18	2.25	1.05
Tanyimboh et al. (2001) [72], Journal of Water Resources Planning and Management	30	129	23.26	2.45	2.08
Farmani et al. (2005) [11], Journal of Water Resources Planning and Management	29	230	12.61	3.13	3.50
Tolson et al. (2004) [73], Journal of Water Resources Planning and Management	27	186	14.52	1.30	1.47
Atkinson et al. (2014) [74], Journal of Water Resources Planning and Management	23	52	44.23	5.95	1.66
Gheisi and Naser (2015) [75], Journal of Water Resources Planning and Management	20	37	54.05	7.27	2.57
Kalungi and Tanyimboh (2003) [76], Reliability Engineering and System Safety	20	91	21.98	2.14	2.27
Giustolisi and Savic (2010) [46], Urban Water Journal	19	105	18.10	6.91	3.98

Notes: LC = Local Citations, GC = Global Citations, NLC = Normalized Local Citations, NGC = Normalized Global Citations.

4.3. Co-Authorship and Collaboration Analysis

4.3.1. Co-Author Analysis

A total of 740 authors were extracted from 34 countries. The ten most influential authors by number of citations and publications are presented in Table 2. The statistics presented in Table 2 are presented based on the 347 articles shortlisted for the analysis. Farmani R. has the highest number of citations (779), followed by Tanyimboh T.T. and Walters G.A. (646 and 609, respectively). Farmani R. has highly cited articles primarily focused on evolutionary algorithms, reliability assessment, and the use of artificial neural networks (ANN) for pipe burst rate prediction. Tanyimboh T.T., who started publishing significantly in 2000 (and even before), has the highest number of publications in the field, with total 20 publications; Farmani R., who started publishing in 2005, has the second highest number of publications, with 11. The major works by Tanyimboh T.T. involve

optimal design of WDNs, reliability assessment, and use of RSMs, such as entropy and resiliency. Walters G.A. has primarily published works on WDN design, considering aspects such as multi-objective design, calibration of WDN models, consideration of uncertainty, tank simulation, maintenance, and rehabilitation as well as risk and vulnerability assessment of WDNs. Jeffrey P. and Yazdani A. started publishing much later, in 2011, and have published only 4 articles in this field. However, they have a considerable number of citations (458 each). Dissemination of professional and technical information to the civil engineering professional was a major goal of the research field. This was accomplished through a variety of publications and information products, including 35 professional and technical journals.

Table 2. Top ten most influential authors ranked by total number of citations.

Author Name	h_Index	TC	NP	PY_Start	Institute	Country
Farmani R.	9	779	11	2005	University of Exeter	United Kingdom
Tanyimboh T.T.	14	646	20	2000	University of the Witwatersrand, Johannesburg	South Africa
Walters G.A.	4	609	4	2000	University of Exeter	United Kingdom
Savic D. A.	5	1061	9	2000	National University of Malaysia	Malaysia
Todini E.	1	517	1	2000	University of Bologna	Italy
Kapelan Z.	7	464	8	2005	Delft University of Technology	Netherlands
Jeffrey P.	4	458	4	2011	Cranfield University	United Kingdom
Yazdani A.	4	458	4	2011	Princeton University	United States
Park N.S.	1	432	1	2004	University of South Florida, Tampa	United States
Prasad T.D.	1	432	1	2004	Gandhi Institute of Technology and Management	India

Notes: TC: Total Citations, NP: Number of Publications, PY_start: Publication start year.

To better understand and visualize the collaboration among the authors, a collaboration map is presented in Figure 5. The map is generated using VOSviewer by setting the minimum number of documents as three and minimum number of citations as 20. The top 30 authors are presented from the shortlisted authors in order to present a clear and readable picture of collaboration. The bigger the node size, the larger the number of publications by the author. The closer the two nodes, the greater the association between the two in terms of co-citation. The thicker the links between two nodes, the stronger the collaboration between the two. Three clusters can be seen; these clusters represent a sub-community with a strong collaboration between the authors. Cluster 1 is comprised of articles on the optimal design of WDNs using evolutionary algorithms and the application of other soft computing tools. Cluster 2 is comprised of articles on optimal WDN design, pipe failure prediction models, and optimal valve placement models. Cluster 3 is comprised of articles on reliability-based design of WDNs and the use of surrogate measures for reliability assessment. In cluster 1, Farmani R. has the highest number of publications, while Savic D.A. and Tanyimboh T.T. have the highest number of publications for cluster 2 and cluster 3, respectively. The links between the various authors represent the collaboration in terms of co-authorship for various documents. The topology appears quite dense for each community, depicting strong collaboration among the authors. However, the sparse topology between the green and blue cluster indicates that more collaborative works should be carried out between the authors of these two communities.

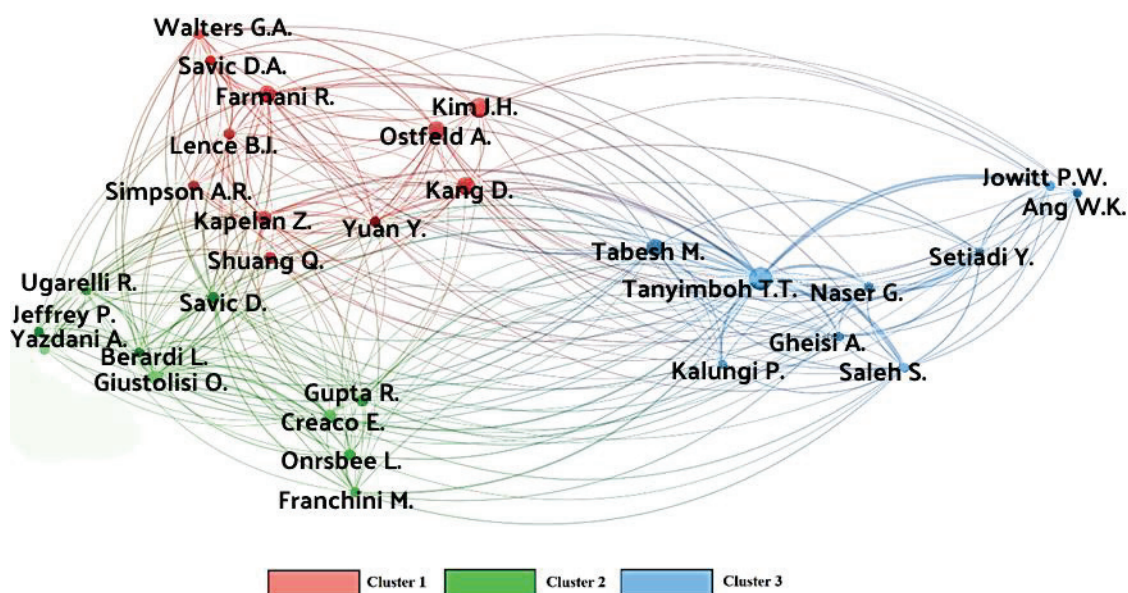


Figure 5. A network map of co-authorship for different authors, node size represents the number of publications for each author and the link thickness represents the collaboration extent.

4.3.2. Countries Network Map

In order to explore the global distribution of publications in this specific research field, a network map for collaboration among various countries was generated. A network of 19 countries is shown in Figure 6. The size of the node represents the production volume by number of documents, while the links represent collaboration between the countries. The distance between two nodes depicts their association by of co-citation. Five clusters can be identified and are presented in Table 3. Cluster 1 is comprised of the US, Iran, Canada, Korea, and Qatar; this cluster has the highest number of publications (273). Cluster 2 includes the UK, Italy, South Africa, Portugal, China, France, and Norway; this cluster has the highest number of citations (4738). The US, UK, and China are the countries with highest number of publications (93, 84, and 76 articles, respectively). The US belongs to cluster 1, while the UK and China belong to cluster 2. This shows that the UK and China strongly collaborate with each other, while the US has minimal collaborations with UK and China. However, the country producing documents with highest number of citations is the UK, followed by Italy and US. The United Kingdom (UK) and the United States (US) are the two countries that have produced the highest number of publications. The substantial number of publications in the UK can be attributed to the fact that the University of Exeter has a strong partnership with the private sector in an attempt to regulate the water laws to reduce leakage levels, improve water quality, and level of service of the water infrastructure [72]. In the US, the American Society of Civil Engineers (ASCE), founded in 1852, is one of the oldest and largest bodies working on the development, maintenance, and enhancement of civil engineering infrastructure. The emerging countries in this research domain are Qatar, Portugal, Norway, and Czech Republic, with 3, 7, 8, and 8 publications, respectively. Portugal and Norway belong to cluster 2, while Qatar and the Czech Republic belong to cluster 1 and 4. While cluster 2 leads in terms of highest number of citations, cluster 3 has the lowest number of citations. It can be inferred that the countries belonging to cluster 4 and 5 (Israel, Poland, Czech Republic, Germany, and Spain) need to collaborate with the countries of other clusters to improve their scientific contributions.

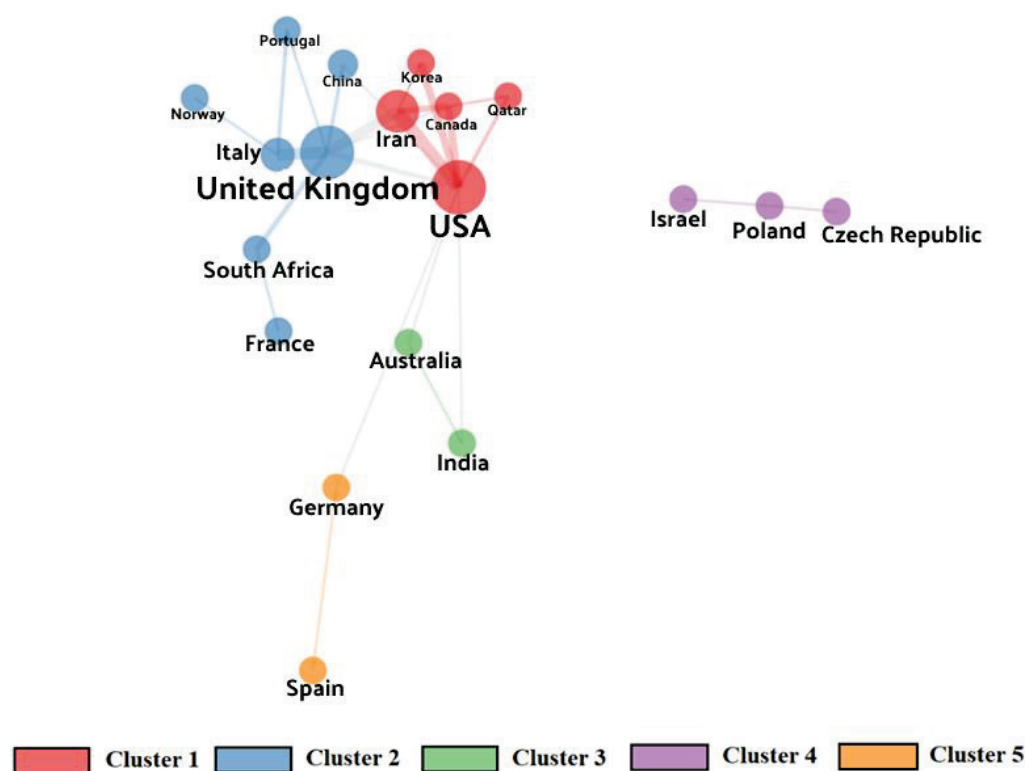


Figure 6. Collaboration network for countries. Node size represents the number of publications and link represents the collaboration among the countries.

Table 3. Countries collaboration, production, and citation data.

Cluster	Country	NP	TC	TNP	TTC
1	United States	93	791	273	1955
	Iran	76	613		
	Canada	39	207		
	Korea	62	344		
	Qatar	3	0		
2	United Kingdom	84	2850	254	4738
	Italy	57	1410		
	South Africa	13	56		
	Portugal	7	16		
	China	76	406		
	France	9	0		
	Norway	8	0		
3	India	34	144	53	239
	Australia	19	95		
4	Poland	26	159	49	476
	Israel	15	290		
	Czech Republic	8	27		
5	Germany	11	30	31	295
	Spain	20	265		

Notes: NP: Number of Publications, TC: Total Citations, TNP: Total Number of Publications for the cluster, TTC: Total Number of Citations for the cluster.

4.3.3. Journal Impact

To study the global distribution of publication among various journals in the field of WDN reliability, Table 4 presents the publication, citations, and indexing for various journals. JWRPM is one of the oldest journals in the field. It began publishing in 2001 and has the highest number of publications and citations in this field. This may be attributed to the fact that JWRPM belongs to ASCE, based in US, one of the countries with highest number of publications. The focus of the journal is advancement in knowledge of civil engineering infrastructures, and so has many publications on the topic of WDNs. Urban Water Journal started publishing in 2000 and has the second highest number of citations. It has 20 publications in the research domain. However, it has a high value of citations per publications. Water Resources Management (WARM) started publishing in this field later than other journals, beginning in 2008, but still has the third highest number of citations and second highest number of publications. It should be noticed JWRPM was established in 1993, WARM in 1987, and the Urban Water Journal in 2000. This may be the reason for lower number of publications in Urban Water Journal.

Table 4. Top ten most cited journals.

Element	TC	TP	CPP	PY_Start
Journal of Water Resources Planning and Management	2608	68	38.35	2001
Urban Water Journal	1032	20	51.6	2000
Water Resources Management	710	36	19.72	2008
Engineering Optimization	472	11	42.91	2000
Reliability Engineering and System Safety	377	11	34.27	2003
Journal of Hydroinformatics	313	10	31.30	2006
Water Resources Research	298	7	42.57	2011
Environmental Modelling and Software	218	4	54.50	2009
Journal of Hydraulic Engineering	207	4	51.75	2007
Water (Switzerland)	182	15	12.13333	2013

Notes: TC: Total citation, TP: Total publication, CPP: Citation per publication, PY_start: Publication start year.

4.4. Co-Citation and Clustering Analysis

4.4.1. Co-Citation Analysis

Co-citation analysis is conducted using bibliometric information of the articles. A Co-citation network is comprised of articles that have been cited by the articles considered for the analysis. Articles belonging to a common theme (commonly cited by a group of authors) are aggregated into one cluster. An author co-citation map was generated using Bibliometrix, as shown in Figure 7. The minimum number of citations was fixed to three and minimum number of articles to 20. As shown in Figure 7, three clusters can be identified. The top ten articles by number of citations from each cluster are presented in Table 5. Betweenness is a measure of how often a node falls on the shortest path between two nodes. Thus, a higher value of betweenness implies that the node has been cited a greater number of times by the authors in the co-citation network.

Cluster 1 belongs to articles on reliability-based design of WDNs and application of optimization techniques. These articles primarily focus on development and application of optimization tools for single and multi-objective reliability-based design of WDNs. One study had the highest page rank in this cluster [8] as it introduced resilience as a surrogate for reliability; this has been employed by numerous studies as an RSM. Another study [20] had the second highest page rank. The article employs the LPG method for the optimal design of WDN, which has been subsequently employed by many studies published in high impact journals. Cluster 2 groups articles focusing on reliability assessment techniques and simulation methods. The highest citation in this cluster was for the EPANET manual [77], that has been used by a substantial number of articles as a simulation tool. The second highest number of citations belongs to a study that introduced a simulation methodology for analyzing the reliability of WDNs [78]. The third highest was for a study that introduced the MCS method for hydraulic reliability estimation this is now one of the most widely used techniques [1]. Cluster 3 groups articles focusing on the use and analysis of various

RSMs as substitute for WDN reliability. In this cluster, the study that introduced a modified resilience index as a surrogate for WDN reliability was the most cited article [10]. A comparative study on the usage of various RSMs, such as entropy, resilience, and network resilience, was presented in one article [79] and, thus, it is one of the widely cited articles. Some studies [71,80,81] presented entropy as a surrogate for WDN reliability while other studies [74,75,79] presented a comparative analysis of the various RSMs.

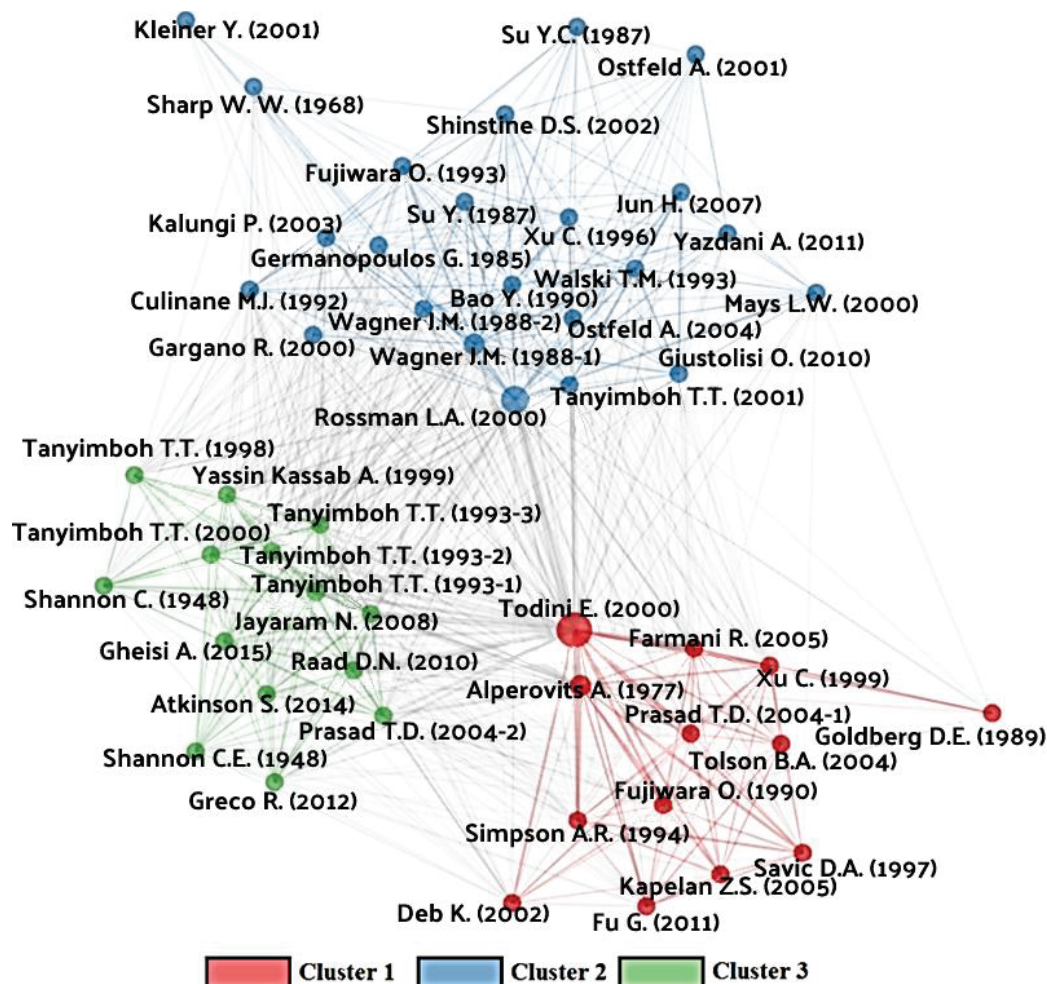


Figure 7. Author co-citation network. These articles have been commonly cited by the original articles. Node size represents the number of articles that have cited the article and links represent that they appear as a common citation in one or more articles.

Table 5. Clustering of co-cited articles.

Article	Cluster	Betweenness	PageRank
Todini (2000) [8]	1	223.332	0.021
Alperovits and Shamir (1977) [20]	1	48.809	0.021
Fujiwara and De Silva (1990) [82]	1	1.811	0.020
Xu and Goulter (1999) [83]	1	11.478	0.020
Simpson et al. (1994) [84]	1	3.457	0.019
Farmani et al. (2005) [11]	1	7.735	0.020
Prasad and Park (2004) [9]	1	6.198	0.019
Savic and Walters (1997) [85]	1	0.577	0.018
Tolson et al. (2004) [73]	1	10.340	0.019
Deb et al. (2002) [86]	1	2.421	0.019
Rossman (2000) [77]	2	96.938	0.024
Wagner et al. (1988) [78]	2	22.916	0.023

Table 5. Cont.

Article	Cluster	Betweenness	PageRank
Bao and Mays (1990) [1]	2	9.589	0.021
Walski (1993) [87]	2	1.870	0.021
Tanyimboh et al. (2001) [72]	2	6.720	0.021
Wagner et al. (1988) [88]	2	5.422	0.023
Ostfeld and Salomons (2004) [89]	2	4.448	0.022
Xu and Goulter (1998) [14]	2	5.327	0.020
Germanopoulos (1985) [90]	2	1.488	0.020
Fujiwara and Ganesharajah (1993) [91]	2	1.670	0.021
Jayaram and Srinivasan (2008) [10]	3	45.350	0.020
Raad et al. (2010) [79]	3	42.236	0.020
Tanyimboh and Templeman (1993) [80]	3	27.807	0.020
Tanyimboh and Templeman (2000) [71]	3	42.326	0.020
Tanyimboh and Templeman (1993) [81]	3	22.664	0.019
Prasad et al. (2004) [92]	3	49.053	0.020
Gheisi and Naser (2015) [75]	3	27.446	0.019
Atkinson et al. (2014) [74]	3	15.626	0.019
Yassin-Kassab et al. (1999) [93]	3	13.915	0.019
Tanyimboh and Templeman (1993) [94]	3	0.080	0.020

4.4.2. Keywords Clustering Analysis

Clustering of articles was conducted based on the most frequently used keywords, as shown in Figure 8. Keywords were aggregated into one cluster if they commonly appeared in a group of articles. The links between different nodes represent that they appear in articles that have collaborations among themselves. The thickness of the links depicts the extent of collaboration, while the distance represents the co-citation. Similar keywords are grouped into one, as they imply the same meaning. The most frequent keywords, their grouping, and the number of occurrences is presented in Table 6. The most widely used keyword was “water distribution network(s)” and related keywords, with 228 occurrences, followed by keywords such as “reliability” and “optimization”, with 116 and 48 occurrences, respectively.

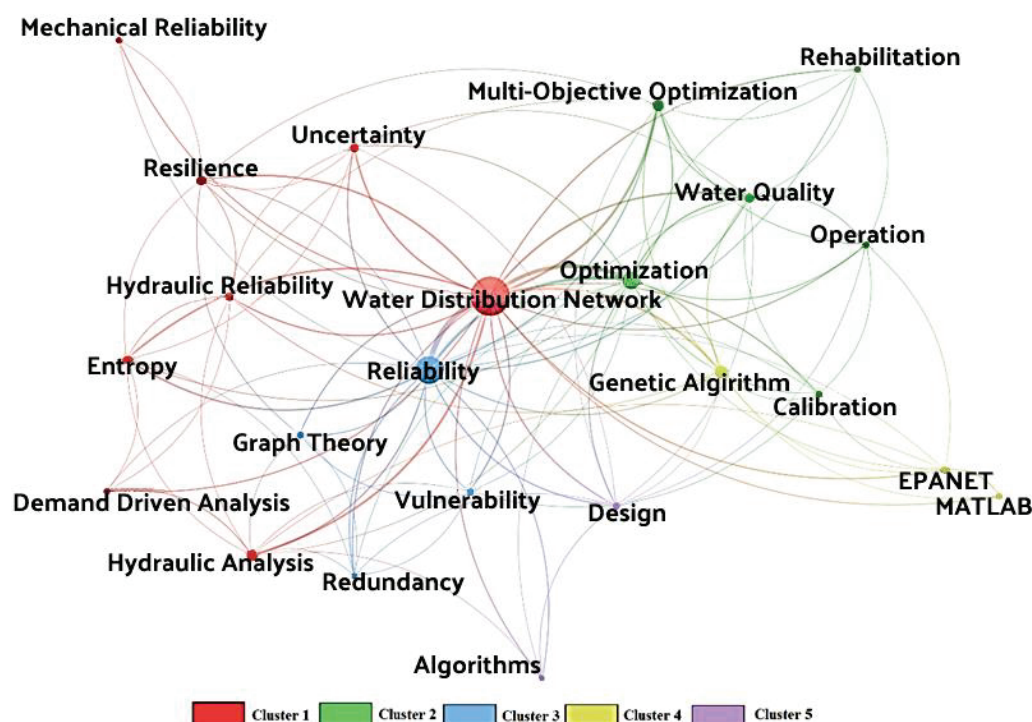


Figure 8. Clusters based on author keywords. Node size represents the number of occurrences of the keyword and the link between two nodes represent their simultaneous occurrences in articles.

Table 6. Frequently used author keywords.

Category	Keyword(s)	Occurrence	Total	Category	Keyword(s)	Occurrence	Total
Water Distribution Network	water supply	11	228	Genetic algorithm	genetic algorithm	15	23
	water supply network	8			genetic algorithms	8	
	WDN	5		Hydraulic analysis	hydraulic analysis	9	18
	water distribution	18			network analysis	9	
	water distribution network	44		Others	resilience	14	
	water distribution networks	48			uncertainty	14	
	water distribution system	38			water quality	14	
	water distribution systems	56			entropy	11	
	pipe networks	7			EPANET	9	
	networks	6			hydraulic reliability	9	
Reliability assessment and analysis	reliability	76	116		design	8	
	reliability analysis	9			vulnerability	8	
	reliability assessment	9			graph theory	7	
	network reliability	9			redundancy	6	
	system reliability	13		rehabilitation	6		
Multi-objective optimization	multi-objective	6	21	algorithms	6		
	multi-objective optimization	10		calibration	5		
	Multi-objective optimization	5		demand-driven analysis	5		
Optimization	optimization	5	48	MATLAB	5		
	optimization	43		mechanical reliability	5		
				operation	5		

Five clusters were identified, as shown in Figure 8. Cluster 1 (red) consists of keywords such as water distribution system(s), hydraulic and mechanical reliability, resilience, uncertainty, entropy, demand driven analysis, hydraulic analysis etc. Thus, the focus of this cluster is on articles concerned with WDN design that consider the aspects of reliability, resilience, entropy, uncertainty etc. The largest node in cluster 2 (green) is optimization, linked with other keywords such as multi-objective optimization, water quality, rehabilitation, and operation. Thus, the articles in this cluster primarily focus on aspects of multi-objective design, operation, and rehabilitation of WDNs, incorporating aspects of optimal design and water quality. Cluster 3 (blue) involves keywords such as reliability, vulnerability, redundancy, and graph theory. Thus, the focus of this cluster is on reliability assessment tools, considering other aspects such as vulnerability and redundancy. Cluster 4 (yellow) is comprised of the keywords “genetic algorithm” (GA), “EPANET”, and “MATLAB”. This shows that the application of GA, linked with EPANET and MATLAB, forms a sizable portion of articles in this field. The fifth and final cluster (purple) is comprised of two keywords, “algorithms” and “design”. Thus, the articles that incorporate various algorithms for optimizing WDNs are presented in this cluster.

Figure 9 shows the evolution of author keywords over time. The color of the node represents the period when it has been most employed, the size of the node represents the number of times the specific keyword was used, and the links represent the co-occurrence in different articles. The use of keywords like entropy, rehabilitation, and algorithms dates to 2005. The use of keywords such as water distribution network(s), optimization, reliability, redundancy, hydraulic analysis seems to gain momentum in 2010. Keywords such as resilience, genetic algorithm, mechanical reliability, and water quality gained importance between 2010 to 2015. Whereas keywords such as hydraulic reliability, uncertainty, and vulnerability evolved hugely in 2015. The keywords significant employed in recent years include EPANET, MATLAB, and calibration.

Mechanical Reliability

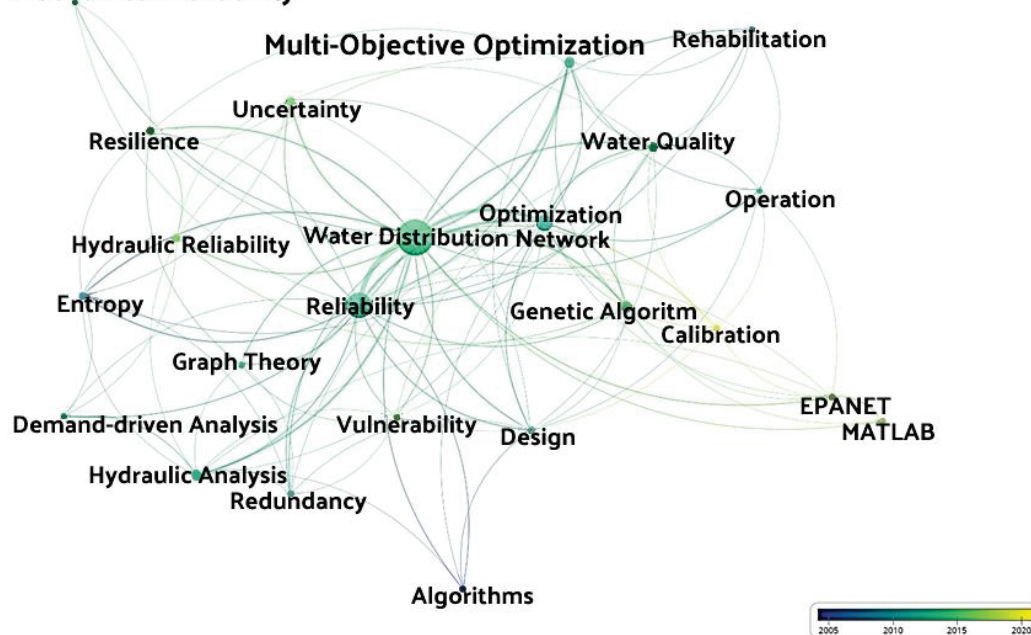


Figure 9. Author keyword evolution over time. Node size represents the number of occurrences of the keyword and the link between two nodes represent their simultaneous occurrences in articles.

4.5. Thematic Clustering and Research Trends

A thematic map is generated using the author keywords to determine the basic themes, niche themes, emerging themes, widely explored, and unexplored themes. The thematic map generated is shown in Figure 10.

The size of a bubble represents the number of articles that have explored the keywords within a theme. Thus, bigger bubble sizes represent a greater number of articles that have explored a particular theme. There are four quadrants in the map. The bottom right quadrant represents the themes with high centrality but low density, constituting the basic themes. These are the themes that have not yet fully developed but play a vital role in the research field. These topics, such as optimization, hydraulic reliability, redundancy, hydraulic analysis etc., constitute the basic themes in this field. The grouping of the keywords represents that consideration of redundancy in hydraulic and demand driven analysis constitute one research field, while multi-objective genetic algorithm considering hydraulic reliability has been employed together to a significant extent. The top right quadrant represents the motor themes; these are the themes with high density and centrality. These themes are fully developed and are vital in the research domain. The consideration of EPANET and MATLAB for mechanical reliability is revealed as a motor theme. This, however, does not necessarily mean that there is no scope for future development in this research domain. The top left quadrant consists of the niche themes that have been fully developed but have less relevance in the research domain. Thus, these themes are of

limited importance for the research field. Topics such as mathematical modeling, Bayesian networks, and cascading failures are niche themes. The bottom left quadrant represents the themes with low density and centrality. These are the topics that have been less developed and thus have exceptionally low relevance. These themes are the emerging themes. Topics such as consideration of CO₂ emissions and energy and cost were underexplored but are emerging themes in the research domain. Network analysis, simulation, and hydraulic models are emerging themes that have been significantly explored. Thus, future works should focus on the consideration of CO₂ emissions, energy, and cost for multi-objective design of WDNs, as well as development of the hydraulic models for network analysis and simulation.

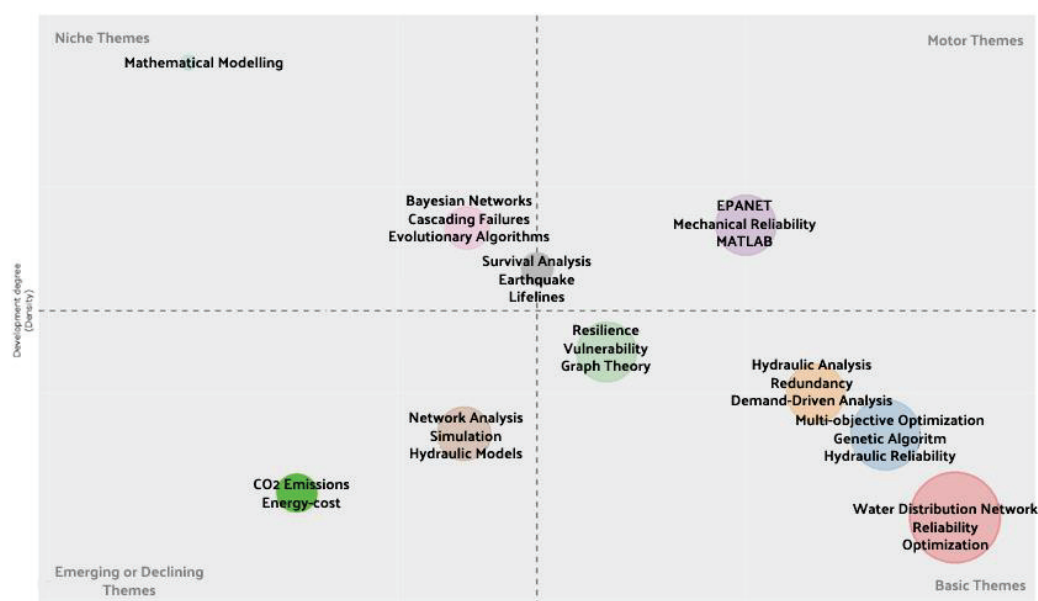


Figure 10. Thematic map based on author keywords. Node size represents the number of articles on a particular theme.

5. Discussion

The results of the bibliometric analysis included several insights into the development of research on the reliability of WDNs. One important finding is that the number of publications in the field has increased over the last two decades. This was discussed in a recent article by [53], who reported an increasing trend in the number of articles produced in the field of WDN design. Article [8] is found to be the most cited article; this finding coincides with the study by [52], which showed that there is an increasing trend in articles considering resilience in WDN design. Farmani R. and Tanyimboh T.T. are the most cited authors; they have published articles on the use of EAs for WDN design, reliability assessment, and the use of RSMs, such as entropy and resiliency. This aligns with the conclusions by [52,53] and the increase in the use of EAs and RSMs for WDN design. Article [77] is found to be the article with the highest page rank in the co-citation network; this is because it is the EPANET manual, that has been employed in numerous studies as the simulation tool. Further exploration of articles is conducted to determine the research areas and the associated research gaps and presented in the following sub sections.

5.1. Major Research Areas

The major research areas are classified into three main categories:

1. Reliability-based single and multi-objective design of WDNs: The works in this category consists of the application and development of improved optimization tools for reliability-based design of WDNs. Various traditional methods, such as LP, NLP, and MINLP, were employed by past studies. Subsequently, advanced techniques,

such as evolutionary algorithms, were employed and were found to possess several advantages over the traditional approaches. Article [11], published in JWRPM, is one of the most cited publications in this field. They formulated the problem as a multi-objective optimization problem for cost minimization and reliability maximization (estimated using resilience as surrogate) using NSGA-II as the optimization tool. Article [95], published in JWRPM, is also a highly cited study employing GA for solving a reliability-based single objective problem: cost minimization keeping reliability as a constraint, considering uncertainty in nodal demands using MCS. Some of the recent publications in this field are [12], that incorporates Self-Adaptive Differential Evolution (SADE) for reliability-based design of WDNs; [96], that presented a Dynamic Adaptive Approach for WDN design; and [97], that presented Self-Adaptive Solution-Space Reduction Algorithm for WDN design.

2. Reliability Assessment Models: Development of reliability assessment techniques are the focus of this field. Some of the oldest techniques include minimum cut set method and simple probabilistic approach for mechanical reliability estimation; and MCS, FORM, and network reliability factor for hydraulic reliability estimation. Later, several RSMs evolved, including resilience, network resilience, and entropy etc., that have the advantage of reduced computational time compared to the traditional approaches. Article [8], published in Urban Water Journal, is one of the most cited articles in the field; it introduced resilience as a surrogate for reliability. Article [9], published in JWRPM, is another highly cited article; it introduced network resilience as an RSM. Several studies focused on performance assessment of one or more of these RSMs [6,13,79,98,99]. Studies reported different findings in terms of the performance of these RSMs under different conditions.
3. Consideration of energy, life cycle cost (LCC), and GHG emissions for expansion and rehabilitation of WDNs: The research in this field focuses on the consideration of aspects such as optimal design and expansion, considering aspects such as LCC, energy consumption, and GHG emissions. Article [11] is a highly cited article that considered LCC in the formulation of WDNs. Article [100] is another highly cited article that presented a model for minimization of LCC and CO₂ emissions and found that minimizing CO₂ emissions can be achieved at a higher LCC. Article [101] presented a dynamic design for the expansion and rehabilitation of WDNs. It found that a dynamic design led to more reliable and lower cost networks. Articles [102,103] presented an enhanced evolutionary algorithm frameworks for the expansion of WDNs considering LCC in their model, and found that this framework led to better solutions when compared to traditional approaches.

5.2. Research Gaps

The major research gaps in each of the research areas are as follows:

1. Reliability-based single and multi-objective design of WDNs: Many optimization tools are provided in the literature. Different studies have shown different tools to be efficient for solving the WDN design problem. There is, however, a need to present a comprehensive review of the various optimization tools and to test their suitability, their advantages, and their drawbacks. The suitability of these algorithms has mostly been tested for consideration of objectives such as cost and reliability. A detailed analysis in terms of how the algorithms will perform on consideration of other objectives, such as GHG emissions, vulnerability etc., should be performed.
2. Reliability Assessment Models: The last two decades have shown an emerging trend in the usage of RSMs. Studies presented and tested these RSMs under various conditions. However, different studies reported different conclusions regarding the suitability of these RSMs. Few studies compared the performance of the various RSMs and the outcomes varied for different studies. Surrogate measures such as entropy, resilience, and network resilience are based on the pressure and flow conditions that would prevail in case of probable failure scenarios. Some studies focused on the consumer's

perspective in terms of the damages caused by incorporating a damage function, when the requirements are not met. Thus, there is a lack of a comprehensive review in terms of the usage of these RSMs, the conditions under which they have been tested and found to be suitable, and their advantages and disadvantages. Findings in terms of which RSMs need further exploration, which RSMs are suitable under what conditions, and which RSMs are unsuitable for some specific conditions must be produced.

3. Consideration of energy, LCC, and GHG emissions for the expansion and rehabilitation of WDNs: Some studies considered the aspects of energy, LCC, and GHG emissions for the optimal expansion and rehabilitation of WDNs. The benefit of considering these aspects in WDN optimization must be tested by acquiring real data in terms of emissions or cost under different scenarios but when implemented at similar locations. Improvements of the WDN expansion techniques are needed, as new optimization approaches continue to be developed.

6. Conclusions and Recommendations

WDN reliability is of the most important and relevant areas of research in the field of safe drinking water supply. This study applied bibliometric analysis and review techniques to explore research themes, trends, and gaps in the topic of WDN reliability. The major insights and conclusions from the bibliometric analysis and content review are as follows:

1. There is an increasing trend in the number of publications in the field of WDN reliability, revealing its growing importance over the past two decades. The number of citations, however, has an alternating increasing and decreasing cycle.
2. Some of the most cited documents are comprised of articles focused on the introduction of RSMs, such as resilience, network resilience etc. This shows that the use of RSMs has gained considerable momentum over the last two decades.
3. Bibliographic coupling led to identification of three major areas of publications: reliability, water distribution networks, and optimization. Thus, cluster 1 is comprised of articles on reliability-based design of WDNs, including aspects such as hydraulic and mechanical failures, uncertainty, vulnerability, and redundancy. Cluster 2 is comprised of articles focused on WDN design and modeling, including aspects such as single and multi-objective optimization, rehabilitation, leakage, calibration, etc. Cluster 3 includes articles on the development and application of various optimization tools for WDN design.
4. Thematic maps revealed that the consideration of cost and energy constitute one of the emerging trends in this field. Detailed analysis of the articles sheds light on the need to assess the suitability and performance of various RSMs in WDN analysis.

The insights and findings from this study can be useful in terms of forming the scope of the upcoming editions for journals and conferences. These can focus on emerging themes such as consideration of CO₂ emissions and energy cost for WDN reliability. The identified research must include employing novel multi-objective optimization tools, extensively exploring and comparing RSMs, and incorporating environmental factors such as GHG emissions in WDN design and expansion. These needs can help formulate the objectives of future research.

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Article

Use of Water and Hygiene Products: A COVID-19 Investigation in Indonesia

Ahmad Komarulzaman ^{1,*}, Widyarani ², Raden Tina Rosmalina ², Diana Rahayuning Wulan ², Umi Hamidah ² and Neni Sintawardani ²

¹ SDGs Center, Universitas Padjadjaran, Jalan Dipati Ukur No. 46, Bandung 40132, Indonesia

² Research Center for Environmental and Clean Technology, National Research and Innovation Agency, KST Samaun Samadikun, Jalan Sangkuriang, Bandung 40135, Indonesia; widyarani@brin.go.id (W.); rade026@brin.go.id (R.T.R.); dian018@brin.go.id (D.R.W.); umih001@brin.go.id (U.H.); neni002@brin.go.id (N.S.)

* Correspondence: ahmad.komarulzaman@unpad.ac.id

Abstract: This study examines the impact of the COVID-19 pandemic on hygiene practices and water consumption in Indonesia. Data were collected through an online survey, supplemented by the official national socio-economic survey. The findings indicate an increase in hygiene practices, particularly handwashing, aligned with health protocols. This behavior led to higher water and hygiene product usage, unaffected by socio-economic factors. Respondents' perception of COVID-19 and compliance with health protocols drove the increase, with older individuals preferring handwashing with water and younger individuals favoring hand sanitizer. Access to improved drinking water remained stagnant, while bottled water consumption rose. This highlights challenges in achieving the SDG 6 targets for safe drinking water. This study stresses the need to address COVID-19 perception to promote better hygiene practices and raises concerns about increased water usage, domestic pollution, and wastewater management during and after the pandemic. These insights could inform policymakers, researchers, and practitioners working in public health and water management to achieve SDG 6 goals amidst the pandemic and beyond.

Keywords: COVID-19 pandemic; water consumption; hygiene product usage; health protocol compliance; Indonesia

1. Introduction

The coronavirus disease (COVID-19) was declared a global pandemic in early 2020, affecting numerous countries worldwide, and even in early 2022, many countries continued to struggle with its spread. Measures like physical distancing, mask-wearing, and hand hygiene, which are crucial in preventing virus spread, have inadvertently posed environmental challenges, particularly in domestic water pollution. These challenges underscore the pandemic's intersection with broader sustainability issues. The Sustainable Development Goals (SDGs) offer a comprehensive framework for addressing global concerns and enhancing human welfare and environmental health [1]. Notably, SDG 6, which emphasizes access to clean water and sanitation, plays a pivotal role in safeguarding public health and other areas [2]. Understanding the pandemic's impact on personal hygiene, water consumption, and water quality is imperative for advancing SDG 6. By examining how the pandemic has influenced these aspects, we can identify strategies and solutions to maintain progress toward the goal of universal access to clean water and sanitation, even in the face of global health crises.

Several studies conducted in various countries, including India, Italy, Morocco, and Indonesia, during the early stages of the pandemic have reported changes in water pollution levels due to reductions in certain activities, i.e., industrial and tourism-related activities [3–9]. Conversely, the closing of workplaces and schools has resulted in increased

domestic water usage [10–12] and changes in hourly water usage patterns [11,13]. Personal hygiene measures, including handwashing and the use of disinfectants, have also influenced water consumption [14] and the usage of cleaning products [15,16]. The active agents in these products may persist in domestic wastewater and, without adequate treatment, can enter the aquatic environment, thereby affecting water quality and posing environmental challenges [17].

While several studies have investigated changes in hand hygiene behavior during the COVID-19 pandemic [18–20], there remains a notable research gap concerning the broader implications of the pandemic on personal hygiene, water consumption, and water quality. This gap is particularly evident in low-income countries with constrained access to water, sanitation, and hygiene (WASH) services. This study aims to address this gap by examining shifts in personal hygiene practices, water utilization patterns, and the use of sanitation products in Indonesia during the COVID-19 pandemic in 2021.

Although the most immediate changes were observed within the initial three years of the pandemic, the repercussions on WASH services may persist for an extended duration [21,22]. Furthermore, the pandemic's influence on hygiene behaviors, adherence to health protocols, and the heightened utilization of water and hygiene products has emerged as a significant determinant of both water demand and quality [22]. By delving into the psychosocial and pandemic-related contexts, the present study seeks to offer valuable insights into the interplay between the pandemic, individual hygiene practices, and the utilization of water and sanitation products.

To address our research objectives, we employed an online questionnaire as the primary data collection method to investigate shifts in personal hygiene practices, alterations in water consumption patterns, and variations in the utilization of sanitation products. The questionnaire was diligently administered to a diverse sample of respondents across Indonesia. Subsequently, the outcomes derived from this survey were meticulously compared with data obtained from the Indonesian National Socio-Economic Survey (SUSENAS). This comprehensive dataset formed the foundation for our rigorous statistical analysis and subsequent data interpretation.

Our study makes a significant contribution to the existing body of knowledge by offering a thorough and insightful examination of the multifaceted impacts of the COVID-19 pandemic on personal hygiene behaviors, water utilization trends, and water quality within the context of Indonesia. The results we have garnered hold intrinsic value for a broad spectrum of stakeholders, ranging from policymakers and water resource managers to public health authorities. These findings offer a profound understanding of the far-reaching consequences of COVID-19 preventive measures on water resources, thereby facilitating the formulation of targeted educational initiatives and hygiene campaigns.

Furthermore, our research underscores the critical importance of prioritizing the sustainability of water and sanitation infrastructure, particularly in low-income nations. This emphasis on long-term infrastructure sustainability is indispensable for ensuring equitable access to clean water and fostering the adoption of safe hygiene practices, especially in the face of widespread health crises like the one posed by the COVID-19 pandemic.

2. Materials and Methods

2.1. COVID-19 and WASH in Indonesia

The first COVID-19 case in Indonesia was reported on 2 March 2020. In order to limit the spread of COVID-19, the first regional movement restriction measure was implemented in April 2020, with different starting points in various regions based on perceived risk. Since then, multiple levels of movement and activity restrictions have been implemented in response to the evolving COVID-19 situation [23].

Until October 2021, Indonesia had experienced two waves of the pandemic [24]. The first wave occurred in January–February 2021, reaching its peak with 14,518 new cases (on 30 January 2021) and 476 deaths (on 28 January 2021) per day. The second wave

occurred in June–August 2021, reaching its peak with 56,757 new cases (on 15 July 2021) and 2069 deaths (on 27 July 2021) per day.

In 2019, prior to the COVID-19 pandemic, merely 83% of the Indonesian population had access to basic sanitation services [25]. Subsequently, a study conducted in Indonesia from May to June 2020, utilizing online surveys, revealed an overarching surge in hand hygiene practices among respondents, alongside a pronounced determination to sustain these improved practices even in a post-pandemic landscape [19]. In light of the new wave of COVID-19 in 2021, the current study aimed to investigate changes in personal hygiene, water usage, and sanitation product usage in 2021.

2.2. Primary Data Collection

A web-based questionnaire was developed to capture changes in water and hygiene product usage patterns before and during the COVID-19 pandemic in Indonesia. Given the mobility restrictions and physical distancing measures in place, an online survey was chosen as the preferred method for data collection. Ethical clearance was obtained from the Committee of Research Clearance Ethics, Indonesian Institute of Sciences (LIPI).

The questionnaire was administered between 22 February 2021 and 24 March 2021 using the KoBotoolbox platform. Due to the limitations of online surveys, convenience sampling was conducted instead of random sampling. The survey link was distributed through various channels such as email, WhatsApp groups, personal contacts of researchers, Twitter, Facebook, and Instagram. Respondents were also encouraged to share the survey link with others through their contact lists and social media. A total of 1093 responses were received through the online survey. After screening for age (18 years old or older), eliminating double responses, and removing extreme outliers, 889 responses were considered for further analysis.

The questionnaire began with a brief description of the study, its purpose, the expected survey duration, and the assurance of anonymity and confidentiality. Participants were required to provide their consent before proceeding with the survey. The estimated time to complete the questionnaire was 10 to 15 min. It consisted of multiple-choice and open-ended questions divided into ten sections, covering topics such as changes in hygiene behavior, water and hygiene product usage patterns, COVID-19-related information, and demographic details. The reliability of the questionnaire was tested through two rounds of piloting before its administration.

The first section of the questionnaire examined changes in the frequency of hygiene activities, including handwashing, showering, and hair washing. The section on changes in water and hygiene product patterns inquired about adjustments in usage frequency and quantity for clean water, hand soap, body (shower) soap, and shampoo. Changes in hygiene activities were assessed using a set of questions employing both qualitative (5-scale answers ranging from greatly decrease to greatly increase) and quantitative approaches. Conversely, changes in water and hygiene product usage were assessed qualitatively, as the quantitative approach might have posed difficulties for respondents to recall precise usage numbers, especially from before the pandemic.

Furthermore, background information was collected to support the analysis, including COVID-19-related information, such as respondents' beliefs and perceptions about COVID-19, compliance with health protocols, and changes in work and income patterns during the pandemic. The questionnaire also included demographic information such as sex, age, education level, and location (provinces). Detailed information on the dataset, outcomes, and questionnaire structure from this web-based survey is accessible in the Supplementary Materials (refer to Tables S1, S2 and S4).

2.3. Indonesian National Socio-Economic Survey

This study utilized the annual Indonesia National Socio-Economic Survey (SUSENAS) cross-sectional data set, which represents the socio-economic characteristics of a large number of households in Indonesia. The survey is conducted every March and September,

with the March survey covering 0.7–1.1 million households and the September survey covering 200,000–286,000 households.

The March SUSENAS consists of two questionnaires: the core questionnaire and the module questionnaire. The core questionnaire collects information on population demographics, education, health, employment, and housing characteristics. The module questionnaire focuses on households' consumption, expenditure, and income. The September SUSENAS includes module questionnaires and special questionnaires, covering areas such as socio-cultural and education, housing and health, and social resilience.

Table 1 provides an overview of the SUSENAS data, including the number of respondents, which represents the total number of households and the population in Indonesia for each year. For this study, a household-level dataset was derived from the SUSENAS surveys conducted between March 2019 and March 2021, representing the period both preceding and during the COVID-19 pandemic. Notably, the first COVID-19 case in Indonesia emerged in March 2020. Consequently, it is important to acknowledge that the 2020 SUSENAS data might not entirely capture alterations in personal hygiene and water consumption behavior specifically associated with COVID-19.

Table 1. Representation of the population and households from the number of respondents in SUSENAS data.

Year	Household Respondent	Representative Households	Representative Population
2019	315,672	71,438,289	267,306,564
2020	334,229	72,792,286	270,315,430
2021	340,032	75,615,091	271,584,775

Source: SUSENAS 2019–2021, authors' calculations.

It is worth emphasizing that our web-based questionnaire and the SUSENAS dataset are distinct entities, each serving complementary roles in our research. Together, they provide unique insights into our study's objectives.

2.4. Statistical Analysis

The collected responses from the questionnaire were analyzed qualitatively and presented as percentages (%). Additionally, a multivariate logistic analysis was conducted to identify factors associated with the increased consumption of water and four hygiene products (hand soap, hand sanitizer, body soap, and shampoo) during the pandemic compared with before. The dependent variable in the analysis was a dummy variable indicating whether the consumption increased (1) or not (0). To accommodate this, we reclassified consumption change from five into two categories—"greatly decrease", "decrease", and "constant" become "not increasing" (coded as 0), while "increase" and "greatly increase" become "increasing" (coded as 1). The analysis considered socio-demographic variables such as sex, age, education, occupation, working pattern during the pandemic, income, and household size. Two indexes, the perception of COVID-19 index and compliance with the health protocol index, were also included in the analysis. The logistic regression results were presented as odds ratios (OR).

In the case of the SUSENAS data, we employed graphical methods to examine changes in personal hygiene and water consumption behavior both prior to and during the COVID-19 pandemic in Indonesia. The expenditure data were adjusted to account for changes in prices (inflation), using constant prices from 2018. This adjustment was made using consumer price index (CPI) data obtained from the Central Bureau of Statistics [26,27]. Additionally, we have provided descriptive statistics, along with results from Mann–Whitney tests, in the Supplementary Materials (Table S3) for reference.

3. Results and Discussion

3.1. Respondents' Characteristics

3.1.1. Demographic

This study included respondents from 31 out of 34 provinces in Indonesia (Figure 1), with a majority of them (82%) coming from six provinces on Java Island, particularly West Java (53%). As Java Island was the main epicenter of COVID-19 spread in Indonesia [28], this allowed us to capture respondents who were likely affected by the pandemic and examine changes in their personal hygiene behaviors. Table 2 presents the demographic characteristics of the respondents. The majority were female (54.9%) with an average age of 39 years and at least a bachelor's degree. The respondents represented a diverse range of occupations, with civil servants, teachers, and employees of state-owned and private companies being the dominant group (58.6%). Most of the respondents belonged to the middle- and upper-income classes (Figure 2a), and over 90% had a high educational level (diploma, bachelor, master, or doctorate). These characteristics align with previous studies in Indonesia [19] and the general pattern of online surveys, where higher education levels [29] and stable employment are commonly observed [30].



Figure 1. Distribution of respondents by province. Source: Online survey result.

Table 2. Demographic characteristics of the respondents ($n = 889$).

Variables	<i>n</i>	%(Mean)
Gender		
Male	401	45.1
Female	488	54.9
Age	889	(39.2)
Educational level		
Not completed primary school	0	0.0
Primary school	1	0.1
Junior high school	2	0.2
Senior high school	75	8.4
Diploma I/II/III	40	4.5
Diploma IV/ Bachelor	395	44.4
Master/ Doctor	376	42.3
Job type		
Unemployed	19	2.1
Student	72	8.1
Housewife	59	6.6
Health worker	13	1.5
Army/ police	0	0.0
Factory worker	14	1.6
Entrepreneur/merchant/service worker	95	10.7
Civil servant/teacher/state-owned & private employees	521	58.6
Farmer/farm labor/construction labor/transportation labor	2	0.2
Other	94	10.6

Source: Online survey result.

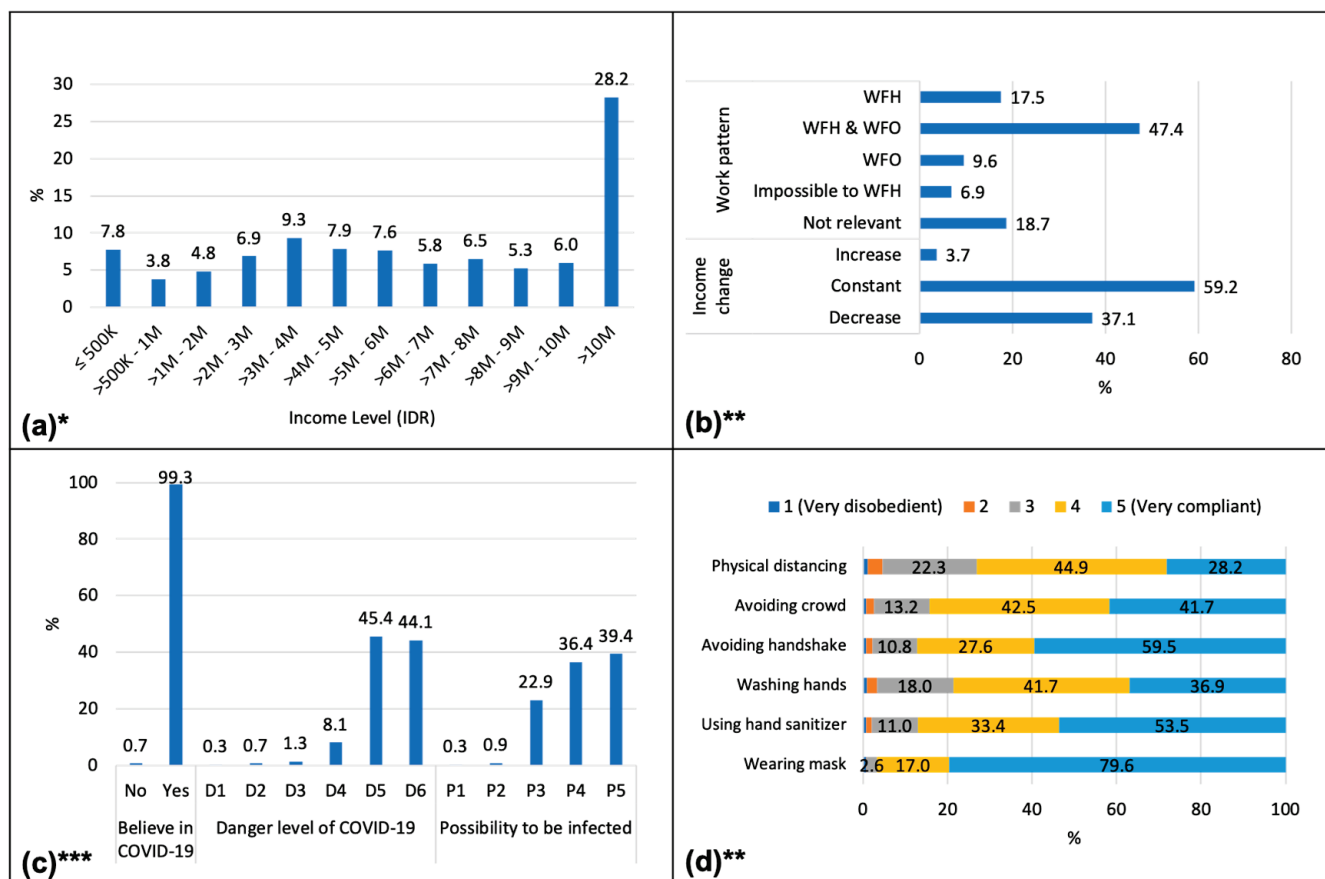


Figure 2. Distribution characteristics of respondents by (a) income group; (b) changes in work and income patterns due to the pandemic; (c) perception of COVID-19; (d) compliance with health protocol-related activities during the pandemic. All figures are expressed in percentage of respondents with a total of 100% ($n = 889$). Notes: * IDR = Indonesian Rupiah ** WFH = working from home, WFO = working from office *** D1 = Not dangerous at all, D6 = Very dangerous. P1 = Very impossible, P5 = Very possible. Due to space constraints, only notable proportions are displayed; for complete details, please refer to the Supplementary Materials (Table S2). Source: Online survey result.

3.1.2. Working during the Pandemic

Additional information was collected regarding the respondents' working patterns, perception of COVID-19, and adherence to health protocols during the pandemic. Although Indonesia did not implement a national lockdown, regional movement and activity restrictions were imposed based on the COVID-19 situation. The first large-scale social restriction (*pembatasan sosial berskala besar*–PSBB) was implemented in West Java, the province in which this study has the highest number of respondents, from 6 May to 25 June 2020. This involved the closure of schools, places of worship, non-essential workplaces, and public facilities. After the PSBB, some relaxations were introduced, such as allowing office buildings to operate at 50% capacity. However, strict compliance with the PSBB guidelines was challenging for some businesses [31], and considerable mobility was still observed during weekends and public holidays [32].

Figure 2b illustrates that 47% of the respondents had a combination of working from home (WFH) and working from the office (WFO). Only 17.5% could exclusively work from home, while another 17.5% were unable to work from home at all. The remaining 18.7% included unemployed individuals, students, and housewives for whom the WFH and WFO options were not applicable.

In terms of income, nearly 60% of the respondents experienced no changes (Figure 2b), which is consistent with the fact that many had stable jobs as civil servants or teachers, or

were employees of state-owned and private companies. However, 37% reported a decrease in their income, particularly entrepreneurs, merchants, service workers, farmers, farm laborers, construction laborers, and transportation laborers. This decrease can be attributed to the vulnerability of private sector companies and small businesses to the economic fluctuations caused by the pandemic [33].

3.1.3. Perception on COVID-19

Figure 2c presents the respondents' perception of COVID-19 and its implications. Almost all respondents believed in the existence of the COVID-19 pandemic. The majority perceived COVID-19 as a dangerous disease and acknowledged the possibility of getting infected. However, a small percentage (0.7%) did not believe in COVID-19, 0.3% did not consider it dangerous, and 0.3% believed it was impossible to be infected. These percentages are higher compared with a similar study conducted in Indonesia in 2020, where only 66.9% of respondents perceived a medium to low risk of infection [19]. The differences in perception can be attributed to the fluctuation in the pandemic situation in Indonesia [19]. Overall, these perceptions of COVID-19 danger and risk influenced the adoption of prevention measures and compliance with health protocols.

3.1.4. Compliance with the Health Protocol

The respondents' compliance with health protocols during the pandemic (Figure 2d) aligns with their perceptions (Figure 2c), particularly regarding wearing masks and avoiding handshakes. Similar to a study conducted in the United States, respondents who perceived a higher risk of infection were more likely to adhere to health protocols, as they recognized the broader impact of the pandemic, including economic consequences [34]. However, some respondents found it challenging to avoid crowds and maintain physical distancing. Interestingly, complying with handwashing recommendations was more difficult compared with using hand sanitizers. This behavior can be attributed to the convenience of hand sanitizers, which are readily available, do not require water, and are less time-consuming [35].

3.2. Access to Sanitation and Drinking Water

The water supply in Indonesia encompasses various sources, including branded bottled water, refillable bottled water, piped water (metered and retailed), protected and unprotected wells, protected and unprotected springs, rainwater, surface water, and others. Among these sources, paid and free water sources exist [36].

To gain insights into sanitation-water sources in Indonesia, this study classified water sources into three categories based on UNICEF and WHO classifications: improved, unimproved, and surface water. Improved water sources include bottled water (branded and refillable), piped water (metered and retailed), protected wells, protected springs, and rainwater. Unimproved water refers to sources such as unprotected wells and springs, while surface water remains categorized as "surface water".

Figure 3a shows that in 2019, 87% of households had access to improved sanitation-water sources, which increased to 88% in 2021. Over the study period, the proportion of households using unimproved and surface water sources decreased. A similar trend was observed in rural areas, except in 2021, where the proportion of households with access to improved sanitation-water sources decreased.

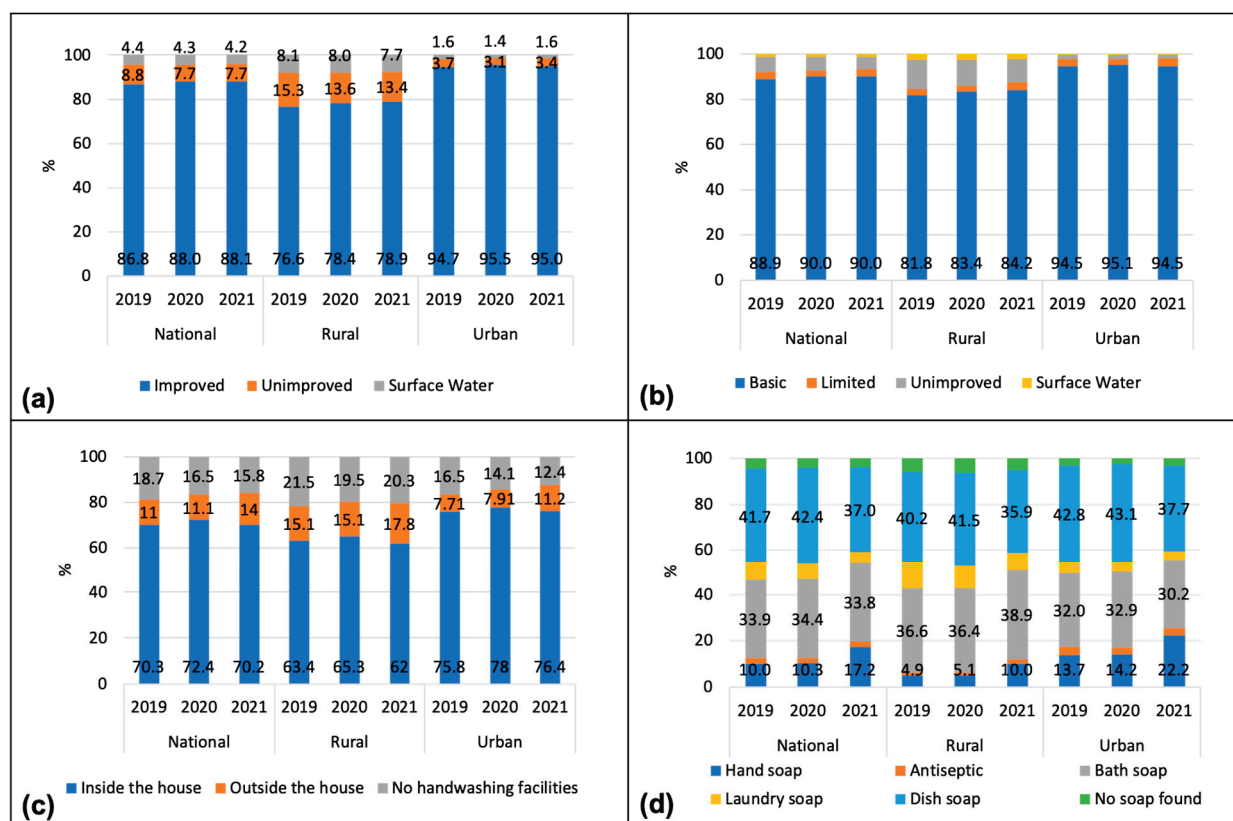


Figure 3. Percentage of households by (a) the accessibility of main sanitation-water sources; (b) the accessibility of main drinking-water sources; (c) the availability of hand washing facilities; (d) the availability of soap in hand washing facilities, in Indonesia 2019–2021 (refer to Table 1 for the description of the *n* values). Notes: All figures show a total of 100%, but due to space constraints, only notable proportions are displayed; for complete details, please refer to the Supplementary Materials (Table S3). Source: SUSENAS 2019–2021, authors' calculations.

Regarding drinking-water sources, this study classified them into four categories: improved, limited, unimproved, and surface water, following UNICEF and WHO classifications. Improved water sources, including branded bottled water, refilled water, piped water (metered and retailed), protected springs, protected wells, and rainwater accessible within 30 min, were the most commonly used by households in Indonesia. The percentage of households using improved drinking water sources increased from 89% at the beginning of the study period to 90% by the end of the study period (Figure 3b). In contrast, in urban areas, the usage of improved drinking-water sources decreased in 2021 due to increased prices, leading households to opt for limited water sources.

The availability of handwashing facilities showed an increasing trend from 2019 to 2021 (Figure 3c). In 2019, the majority of households in Indonesia had handwashing facilities, with 70% located inside the house and 11% located outside. In 2020, approximately 72% of households had handwashing facilities inside and 11% outside. In 2021, the availability of handwashing facilities outside the house increased to 14%, while the percentage of facilities inside decreased to 70%.

Similar patterns were observed in rural and urban areas. In 2020, there was an increase in the percentage of households with handwashing facilities inside and outside the house. However, in 2021, the percentage of households with facilities inside decreased, while those with facilities outside increased, possibly due to the recommendation of washing hands before entering the house after traveling [37].

The availability of water and soap in handwashing facilities also increased during the pandemic. In 2021, 98% of households had water available in their handwashing facilities, and the percentage of soap availability consistently increased over the study period.

Figure 3d shows that dish soap, bath soap, and hand soap were the most common types of soap found in household handwashing facilities. Dish soap availability reached 42% in 2019, bath soap availability reached 34%, and hand soap availability reached 10%. These figures consistently increased during the study period.

3.3. Water and Hygiene Products Use Pattern

This section highlights the main findings of the study regarding changes in water and hygiene product usage patterns during the pandemic compared with before. The analysis also incorporates socio-economic data obtained from SUSENAS to provide a comprehensive understanding of the observed changes.

3.3.1. Changes in Hygiene Activities Behavior

The respondents reported a substantial increase in hygiene activities during the pandemic compared with before, with a particular focus on handwashing (Figure 4a). Prior to the pandemic, respondents washed their hands an average of 6.6 times per day, which then doubled to 13.6 times per day during the pandemic (Figure 5). Similar findings were reported in another study, where handwashing frequency of less than 4 and 4–8 times per day increased to 8–12 times per day during the pandemic [19].

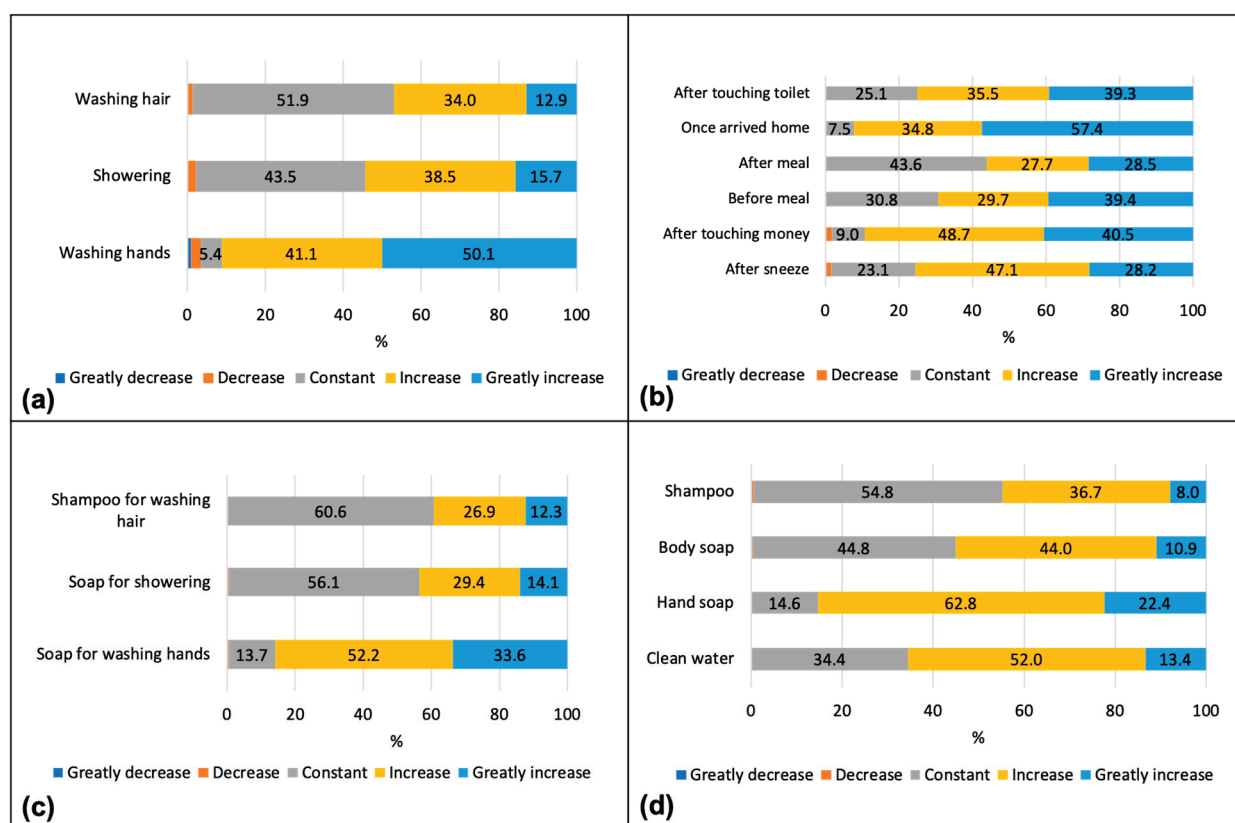


Figure 4. Changes in (a) frequencies of hygiene activities; (b) handwashing frequency; (c) hygiene products use frequency; (d) consumption/purchase quantity of water and hygiene product use, during the pandemic in comparison to before the pandemic. All figures are expressed in percentage of respondents with a total of 100% ($n = 889$). Due to space constraints, only notable proportions are displayed; for complete details, please refer to the Supplementary Materials (Table S2). Source: Online survey result.

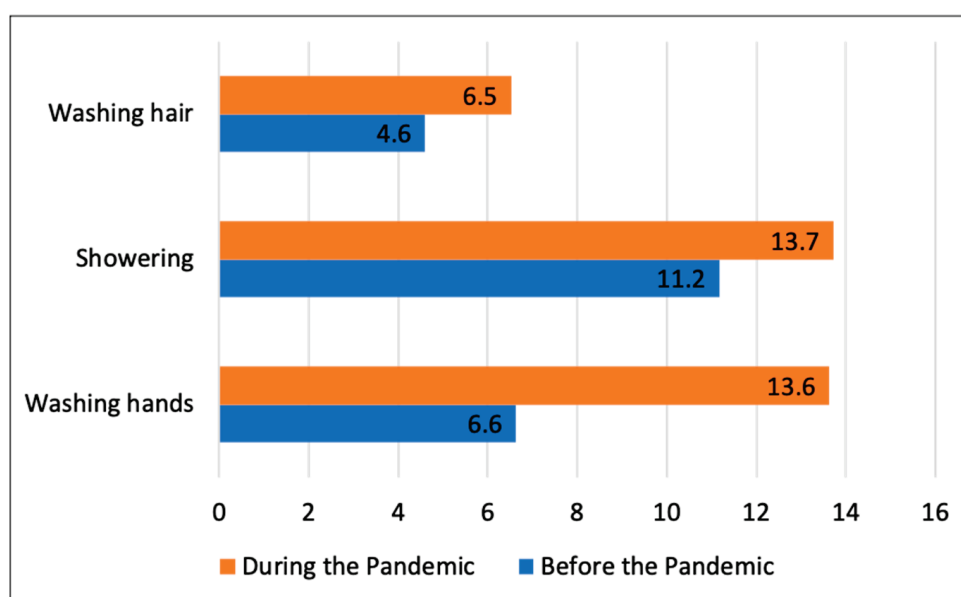


Figure 5. Average frequency of hygiene activities during and before the pandemic ($n = 889$). Source: Online survey result.

The increase in handwashing frequency was particularly noticeable upon arriving at home and after handling money (Figure 4b). There were also smaller increases observed for handwashing after touching the toilet, before meals, after sneezing, and after meals. This increase in handwashing frequency aligns with the rise in households with handwashing facilities during the pandemic (Figure 3c). Similar patterns were observed in studies conducted in Brazil and Saudi Arabia [38,39]. The heightened focus on hygiene activities during the COVID-19 pandemic can be attributed to the preventive measures aimed at maintaining hand cleanliness [39].

While some respondents reported an increased frequency of showering and hair washing, a notable portion (43.5%) reported no change in showering frequency, and (52%) reported no change in hair washing frequency (Figure 4a). On average, the frequency of showering slightly increased from 11.2 times per week before the pandemic to 13.7 times per week (twice a day) during the pandemic (Figure 5). Similarly, the average frequency of hair washing increased from 4.6 times per week before the pandemic to 6.5 times per week (once a day) during the pandemic. These findings are consistent with a study conducted in Saudi Arabia, where there was an increase in showering and hair washing frequency during the COVID-19 pandemic, likely due to preventive measures [39]. This increase in hygiene activities during the pandemic might result in increased water and hygiene product consumption.

3.3.2. Changes in Water and Hygiene Products Use

To assess the changes in water and hygiene product usage, respondents were asked about the frequency of using hygiene products and the quantity of water and hygiene products consumed or purchased. Figure 4c shows that there was a substantial increase in the use of hand soap, with 85.6% of respondents reporting an increase (52.2%) or a great increase (33.6%). The use of body soap (for showering) also slightly increased, reported by 43.4% of respondents. The use of shampoo showed an increase and great increase among 26.9% and 12.3% of respondents, respectively.

Regarding the quantity of water and hygiene product consumption/purchase, Figure 4d indicates a substantial increase in the consumption of hand soap, with 62.8% reporting an increase and 22.4% reporting a great increase. Consumption quantities of body soap and shampoo also increased, although to a lesser extent. The consumption of clean water was reported to increase by over half of the respondents and greatly increase by 13.4%

of the respondents. Similar trends were observed in studies conducted in Saudi Arabia and England, where water consumption increased during the lockdown period due to increased hygiene practices and remote work [10,40].

In terms of household behavior, SUSENAS data show that the availability of hand soap at handwashing facilities substantially increased from 10% in early 2020 to 17% in 2021 (Figure 3d). This shift indicates a preference for hand soap and antiseptic over dish soap and bath soap. The proportion of households with bath soap and dish soap decreased in 2021 compared with 2019. These findings align with the results of the online survey (Figure 4c) that showed a substantial increase in the use of hand soap.

Figure 6a presents the average household expenditure on bath soap, toothpaste, toothbrush, and shampoo. Notably, there was a slight increase in expenditure (0.18%) between 2019 and 2020, and this trend continued with a more pronounced rise of 5.9% between 2020 and 2021. Similar trends were observed in both urban and rural areas. It is worth noting that this surge in expenditure between 2020 and 2021 aligns seamlessly with the findings from the online survey (depicted in Figure 4d), which indicated an increased consumption of body soap and shampoo during this pandemic period.

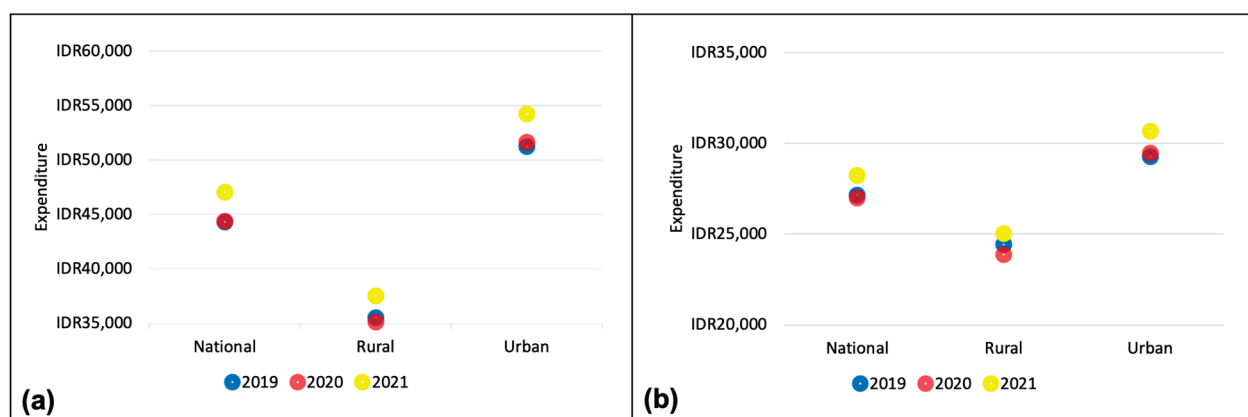


Figure 6. Average monthly expenditure on (a) bath soap/toothbrush/toothpaste/shampoo; (b) laundry soap, in Indonesia 2019–2021 (please refer to Table 1 for the description of the *n* values). Notes: IDR = Indonesian Rupiah. Source: SUSENAS 2019–2021, authors' calculations.

Figure 6b shows the household average monthly expenditure on laundry soap, which increased during the study period, primarily in urban areas. This increase could be attributed to the rise in showering frequency during the pandemic caused by the rapid increase in COVID-19 cases in the urban area (Figure 5). However, it is important to note that SUSENAS only provides expenditure information and not consumption quantities for these hygiene products.

Regarding piped water consumption, Figure 7a illustrates that at the national and urban levels, the average monthly quantity and expenditure increased in 2020, while a different trend occurred in rural areas, where both decreased over the study period. In 2021, the average monthly quantity of piped water consumption decreased at the national, urban, and rural levels. However, the expenditure on piped water still increased at the national and urban levels due to higher consumption and expenditure in the higher expenditure (decil) category. These findings align with previous studies indicating that piped water is more accessible to middle and upper-class households, while poorer households rely on free water sources [36].

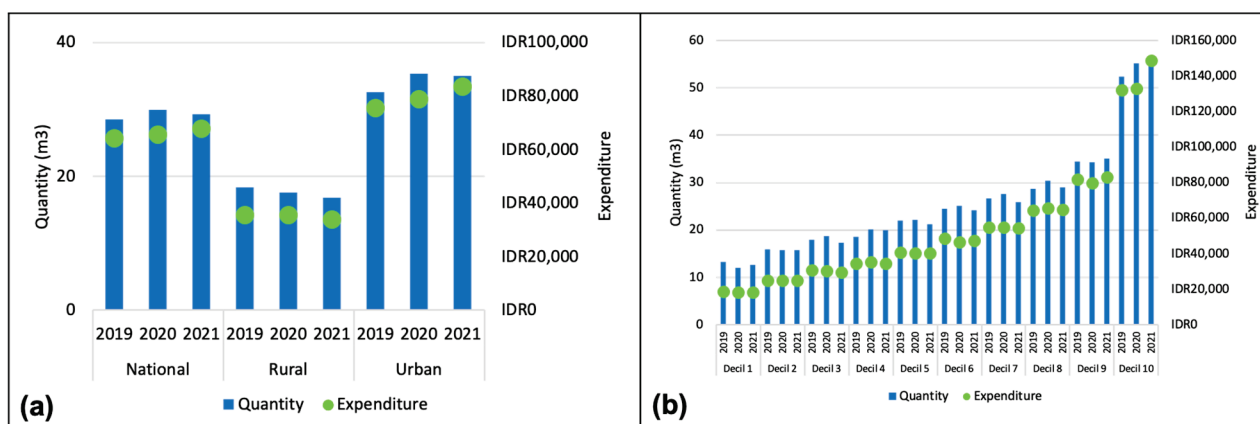


Figure 7. Average monthly quantity and expenditure on (a) piped water; (b) piped water based on household expenditure category, in Indonesia 2019–2021 (please refer to Table 1 for the description of the n values). Notes: IDR = Indonesian Rupiah. Source: SUSENAS 2019–2021, authors' calculations.

This study also examined the quantity and expenditure of bottled water consumption. At the national, urban, and rural levels, the average quantity of 19 L-bottled water increased in 2021, accompanied by a slight increase in expenditure (Figure 8a). This trend was likely driven by the growing demand for clean and more convenient sources of drinking water during the COVID-19 pandemic [41,42]. The greater increase in quantity compared with the rise in expenditure suggests that the household may have transitioned from branded (more expensive) bottled water to refillable (cheaper) bottled water in order to meet their drinking water needs while managing reduced income during the pandemic.

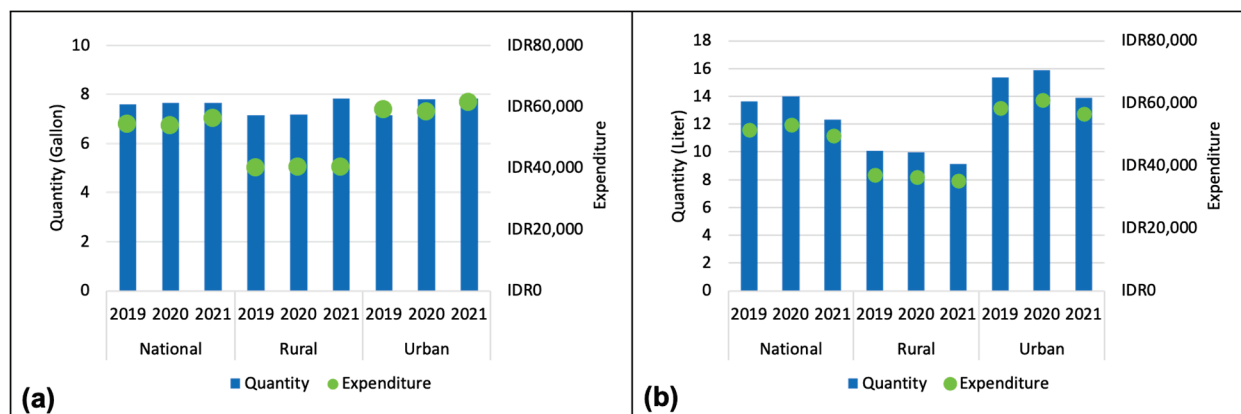


Figure 8. Changes in quantity and expenditure of (a) 19 L-bottled water; (b) liter-bottled water, in the pandemic in comparison with before the pandemic based on household expenditure category (refer to Table 1 for the description of the n values). Notes: IDR = Indonesian Rupiah. Source: SUSENAS 2019–2021, authors' calculations.

At the national level, the average expenditure on bottled water in smaller sizes (up to 1.5 L) increased in 2020, driven by higher consumption quantities (Figure 8b). In 2021, there was a decrease in the average quantity of consumption, followed by a decrease in average expenditure. This could be attributed to reduced mobility during the COVID-19 pandemic, leading to a decrease in the purchase of smaller-sized bottled water for traveling.

Overall, the findings indicate substantial changes in water and hygiene product use during the pandemic. There was an increase in the frequency and quantity of hand soap, body soap, shampoo, and clean water consumption. The availability of hand soap at handwashing facilities also showed a substantial increase. Expenditure on bath soap, toothpaste, toothbrushes, and shampoo increased over time. Piped water consumption

exhibited varying trends between urban and rural areas, with a decrease in quantity but an increase in expenditure. The consumption and expenditure of bottled water, both in larger and smaller sizes, increased in most areas, except for rural areas where a decrease in quantity was observed. These findings highlight the impact of the pandemic on water and hygiene behaviors, reflecting the increased emphasis on cleanliness and hygiene practices during this period.

3.4. Factor Associated with Water and Hygiene Product Use

Table 3 presents the results of (multivariate) logistic regression analysis on the factors influencing the increase in water and hygiene product use during the pandemic. Age significantly affected the increase in water use and hand sanitizer use. For each one-year increase in age, there was a 2.1% higher likelihood of using more water and a 3.8% lower likelihood of using more hand sanitizer. However, age did not significantly influence the use of more hand soap, body soap, and shampoo. This suggests that older respondents preferred washing hands with water rather than using hand sanitizer. Older individuals tended to wash their hands in various situations due to a higher perceived personal risk of COVID-19 infection [43]. On the other hand, younger individuals may have preferred hand sanitizer due to lifestyle factors and convenience. Access to handwashing facilities plays a role in this preference [44].

Table 3. Factors influencing higher quantity use of water and hygiene product, odd ratio (confidence interval).

Variables	M1 Clean Water OR (CI)	M2 Hand Soap OR (CI)	M3 Hand Sanitizer OR (CI)	M4 Body Soap OR (CI)	M5 Shampoo OR (CI)
<i>Sex</i> ^a					
Male (ref)	1	1	1	1	1
Female	1.099 (0.809–1.494)	1.084 (0.717–1.638)	1.083 (0.622–1.886)	0.872 (0.648–1.172)	0.867 (0.642–1.170)
<i>Age</i> ^b	1.021 ** (1.005–1.037)	0.998 (0.978–1.018)	0.962 *** (0.938–0.986)	1.009 (0.995–1.024)	1.003 (0.989–1.018)
<i>Education</i> ^a					
Up to high school (ref)	1	1	1	1	1
University	1.077 (0.603–1.923)	1.215 (0.602–2.453)	2.288 ** (1.020–5.134)	0.846 (0.479–1.496)	0.926 (0.518–1.654)
<i>Occupation</i> ^a					
Unemployed (ref)	1	1	1	1	1
Health personnel	1.661 (0.389–7.092)	0.465 (0.0958–2.262)	0.604 (0.0571–6.387)	1.695 (0.449–6.403)	0.896 (0.247–3.247)
Worker and Merchant	1.210 (0.604–2.423)	0.991 (0.402–2.442)	0.780 (0.262–2.325)	0.910 (0.484–1.712)	1.489 (0.784–2.828)
Civil Servant	0.929 (0.496–1.739)	1.230 (0.526–2.876)	0.752 (0.267–2.120)	0.934 (0.524–1.663)	1.247 (0.694–2.239)
Others	0.628 (0.322–1.225)	0.853 (0.357–2.040)	0.682 (0.238–1.953)	0.879 (0.469–1.648)	1.021 (0.538–1.940)
<i>Working pattern</i> ^c					
WFO (ref)	1	1	1	1	1
WFH and WFO	1.122 (0.683–1.843)	1.131 (0.586–2.184)	0.788 (0.352–1.763)	0.680 (0.423–1.093)	0.756 (0.468–1.220)
WFH	0.910 (0.596–1.390)	1.043 (0.595–1.827)	1.528 (0.701–3.329)	0.895 (0.593–1.350)	0.899 (0.595–1.358)

Table 3. Cont.

Variables	M1 Clean Water OR (CI)	M2 Hand Soap OR (CI)	M3 Hand Sanitizer OR (CI)	M4 Body Soap OR (CI)	M5 Shampoo OR (CI)
<i>Monthly Income</i> ^c					
≤0.5 M (ref)	1	1	1	1	1
0.5 M–1 M	1.218 (0.501–2.962)	1.096 (0.384–3.126)	0.451 (0.144–1.410)	1.328 (0.560–3.148)	1.569 (0.649–3.794)
1 M–2 M	1.674 (0.684–4.099)	1.439 (0.510–4.059)	1.539 (0.445–5.324)	1.040 (0.448–2.419)	2.057 (0.859–4.925)
2 M–3 M	1.216 (0.525–2.815)	3.319 * (0.969–11.36)	1.744 (0.437–6.961)	1.004 (0.452–2.231)	1.224 (0.540–2.772)
3 M–4 M	1.265 (0.564–2.835)	1.300 (0.481–3.509)	1.437 (0.417–4.952)	1.153 (0.534–2.492)	1.223 (0.556–2.692)
4 M–5 M	0.958 (0.418–2.194)	1.615 (0.549–4.753)	2.533 (0.591–10.85)	0.901 (0.406–2.000)	1.316 (0.584–2.966)
5 M–6 M	1.157 (0.491–2.726)	1.152 (0.396–3.356)	2.329 (0.535–10.15)	1.262 (0.553–2.879)	1.523 (0.663–3.497)
6 M–7 M	0.892 (0.364–2.184)	2.263 (0.633–8.084)	2.905 (0.554–15.24)	0.748 (0.316–1.772)	0.655 (0.267–1.602)
7 M–8 M	1.542 (0.622–3.824)	2.776 (0.770–10.01)	0.994 (0.260–3.800)	1.242 (0.528–2.921)	1.205 (0.508–2.855)
8 M–9 M	0.840 (0.334–2.114)	0.928 (0.293–2.936)	1.789 (0.352–9.094)	0.558 (0.228–1.366)	0.719 (0.287–1.805)
9 M–10 M	1.160 (0.461–2.920)	1.947 (0.548–6.919)	5.803 (0.608–55.41)	0.546 (0.229–1.303)	0.806 (0.331–1.959)
>10 M	0.870 (0.408–1.854)	1.234 (0.480–3.173)	2.381 (0.703–8.059)	0.733 (0.355–1.511)	0.774 (0.367–1.629)
Household size ^b	1.053 (0.985–1.126)	1.049 (0.947–1.162)	1.136 (0.969–1.332)	1.023 (0.972–1.078)	1.019 (0.971–1.069)
Compliance index ^b	4.386 *** (1.453–13.24)	13.552 *** (3.589–51.17)	10.083 *** (2.074–49.02)	6.680 *** (2.186–20.42)	9.594 *** (2.917–31.55)
Perception index ^b	4.587 * (0.855–24.60)	4.869 * (0.741–31.97)	89.892 *** (9.243–874.2)	8.530 ** (1.497–48.58)	24.957 *** (3.657–170.3)
Constant	0.047 *** (0.009–0.238)	0.074 *** (0.012–0.476)	0.031 *** (0.003–0.298)	0.042 *** (0.008–0.220)	0.006 *** (0.001–0.037)
Observations	889	889	889	889	889

Notes: The coefficients represent odds ratio of increase in water and hygiene product use during the pandemic. A 95% confidence interval in parentheses. Ref: reference category. Dummy variable ^a, continuous variable ^b, categorical variable ^c. Significance level at $p < 0.01$ ***, $p < 0.05$ **, $p < 0.1$ *. Source: online survey result, authors' calculations.

Respondents with a university education were 2.3 times more likely to increase their use of hand sanitizer during the pandemic compared with those without a university education. Higher education levels generally correspond to higher mobility and better access to hand sanitizer [45,46]. This finding could also be attributed to the understanding of hand sanitizer efficacy among individuals with higher education. However, education did not have a significant effect on water and other hygiene products. Similar findings were observed in a study conducted in Indonesia in 2020, where the educational characteristics of the respondents were limited and dominated by the highly educated [19].

The increased use of water and hygiene products was positively influenced by respondents' perception of COVID-19 and their compliance with health protocols. Respondents who perceived COVID-19 as dangerous and believed they were susceptible to infection were more likely to increase their use of water and hygiene products during the pandemic. Moreover, higher compliance with health protocols was associated with a higher likelihood of increased water and hygiene product use. These findings align with a similar study conducted in Indonesia [19].

Other socio-demographic variables such as gender, occupation, working pattern, income, and household size did not significantly affect the likelihood of increasing water and hygiene product use during the pandemic. The increased use of water and hygiene

products was not strongly influenced by economic status, work location, or household size but rather by adherence to health protocols and the level of concern about COVID-19.

4. Conclusions, Limitations, and Future Research Directions

This study's findings support the hypothesis that the pandemic has led to increased hygiene practices, particularly handwashing, in line with health protocols. This has resulted in a higher consumption of water and hygiene products. Socio-economic factors such as sex, income, occupation, working pattern, and household size did not significantly influence this increase. Instead, it was influenced by respondents' perception of COVID-19 (perceived danger and susceptibility to infection) and their compliance with health protocols. Age and knowledge about the efficacy and safety of hand sanitizer also played a role. Future research should explore lifestyle choices related to hand sanitizer preference and access to clean water during and after the pandemic. These findings highlight the importance of addressing COVID-19 perception in promoting better hygiene practices, and also raise concerns about increased water usage, domestic water pollution, and wastewater management during and after COVID-19.

This study reveals that access to improved drinking water sources in Indonesia remained stagnant throughout the pandemic, while there was an increase in the consumption and expenditure of bottled water. In developing countries like Indonesia, bottled water often comes in the form of refillable bottled water that has questionable quality, posing considerable health risks [47]. This presents a formidable challenge to Indonesia's pursuit of the global SDG 6 objective. Access to improved drinking water is fundamental to achieving the goal of "safely managed drinking water" as outlined in SDG 6.1.1. Moreover, the increased reliance on bottled water may stem from individuals perceiving it as safer or more convenient. However, it is crucial to emphasize that the escalated consumption of bottled water results in a proliferation of plastic waste, incurring both economic and environmental costs.

Conversely, this study highlights enhancements in handwashing facilities, soap availability, and the utilization of hygiene products during the pandemic. These discoveries contribute to the advancement of SDG 6.2.1, specifically addressing the "sanitation and handwashing facility" progress in Indonesia. Additionally, comprehending the role of SDG 6 in managing the COVID-19 pandemic, its influence on progress, and the imperative steps for accelerating SDG 6 development within this context holds paramount importance.

This study's robustness lies in its integration of an online survey with an analysis derived from a comprehensive national socio-economic survey, bolstering its reliability. However, it is crucial to acknowledge the limitations of the online survey, which primarily attracted highly educated and middle- to upper-class respondents due to the recruitment methods used. Furthermore, the overrepresentation of respondents from Java Island may restrict the generalizability of the study's outcomes to the broader Indonesian population. Caution is warranted when extrapolating these results. Another limitation pertains to the self-reported nature of the survey, as some respondents may have tailored their responses to present themselves as more 'hygienic,' potentially impacting the data. Nevertheless, the study's reliability is strengthened by its incorporation of insights from the comprehensive national socio-economic survey, ensuring a more holistic understanding of the subject matter.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w15193405/s1>, Table S1: Demographics of Web-based Questionnaire Respondents; Table S2: Web-based Questionnaire Results; Table S3: Descriptive Statistics and Mann-Whitney Tests of SUSENAS Data; Table S4: Web-based Questionnaire Form.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author, [A.K.], upon reasonable request.

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Article

Hybrid Optimization Algorithms of Firefly with GA and PSO for the Optimal Design of Water Distribution Networks

Riham Ezzeldin ¹, Martina Zelenakova ^{2,*}, Hany F. Abd-Elhamid ^{3,4}, Katarzyna Pietrucha-Urbanik ^{4,5} and Samer Elabd ¹

¹ Irrigation and Hydraulics Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt

² Institute of Sustainable and Circular Construction, Faculty of Civil Engineering, Technical University of Košice, 042 00 Košice, Slovakia

³ Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt; hany_farhat2003@yahoo.com

⁴ Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Košice, 042 00 Košice, Slovakia; hany.abdelhamid@tuke.sk

⁵ Department of Water Supply and Sewage Systems, Faculty of Civil and Environmental Engineering and Architecture, Rzeszow University of Technology, 35-959 Rzeszow, Poland; kpiet@prz.edu.pl

* Correspondence: martina.zelenakova@tuke.sk

Abstract: A novel two-hybrid optimization model of particle swarm optimization (FAPSO) and firefly algorithm with genetic algorithm (FAGA) are introduced to improve the performance of the conventional firefly algorithm for the least cost design of water distribution networks. The performance of the models is tested through application to three of the well-known benchmark networks available in the literature and also to the real case study of the El-Mostakbal City network, Ismailia, Egypt. The performance of the different algorithms was determined by evaluating the minimum, maximum, mean and standard deviation of costs, the function evaluation number, the consumed computational time for 1000 evaluations and the success rate calculated using the fuzzy logic concept for different optimal solutions slightly greater than the known optimal solution (by about 1.0% and 2.0%) were utilized for testing the convergence and search capabilities of the models. It was found that the FAGA model is superior to the standard firefly and FAPSO models in exploring the search space, exploiting the promising areas and convergence to the optimal solution and can be considered as a reasonable optimization technique for the management of water distribution networks.

Keywords: water distribution networks; hybrid optimization; firefly algorithm; genetic algorithm; particle swarm optimization; performance evaluation

1. Introduction

Water distribution networks are one of the most important necessary infrastructures for the development of countries worldwide. Huge investment is required for the construction of such networks, and a relatively small decrease in this cost leads to a considerable total saving which can be achieved by selecting the pipe diameters from a set of available market sizes to minimize the total construction cost. This process is referred to as the optimal design of water distribution networks. Numerous optimization techniques were and are still being developed for such purpose of searching in a very large non-differentiable, and nonconvex design space. It is a discrete type of problem and very computational demand. However, still, there is no agreement on what optimization method is best for a particular design problem, and considerable research challenges remain essential [1].

Standard optimization techniques early developed include linear programming (LP) applied only to linear objective functions, equations and constraints, nonlinear programming (NLP) to deal with nonlinear problems and dynamic programming (DP) to solve stochastic and nonlinear problems. These techniques get stuck in local optimum solutions

and do not guarantee global optimum performance. Besides, limitations when applied to problems with high dimensionality, uncertainty and requires high computational time [2].

In the last few decades, heuristic and metaheuristic techniques have been developed to overcome such limitations. Among these techniques are genetic algorithm, particle swarm optimization and firefly algorithm. The genetic algorithm (GA), first introduced by Holland [3], is the most popular evolutionary population-based algorithm which has been adopted in many complex optimization problems in water resources applications. Many researchers have attempted to improve the computational efficiency of the algorithm. Reza et al. 2017 [4] introduced the bounded genetic algorithm (B-GA) model to reduce the search space by decreasing the number of available pipe sizes that can be used for each of the network pipes. Recently, Sangroula et al. [5] introduced the smart optimization program for water distribution networks (SOP-WDN) which is based on a genetic algorithm linked with the EPANET hydraulic simulation solver. Particle swarm optimization PSO first introduced by Eberhart and Kennedy [6], is inspired by the behavior of a flock of birds and has been widely used in various optimization problems in different fields because of its simplicity and the few parameters that have to be adjusted.

Most of the optimization techniques were introduced in their standard form, then followed by different modifications that were found necessary to improve their reliability, robustness and convergence so that they become more and more effective for the optimization of water distribution networks. Among these modifications is the hybridization of different optimization algorithms, which recently have been widely considered by many researchers for performance improvement. (bacterial foraging, genetic algorithm and ant colony, [7]) (particle swarm and Hooke–Jeeves, [8]), (particle swarm and tabu search, [9]), (particle swarm optimization and cuckoo search, [10]), (grasshopper optimization algorithm and genetic algorithm, [11]). The firefly optimization algorithm has received considerable attention through being hybridized with other algorithms for different applications, as shown in Table 1, which summarizes the different hybrid firefly models.

Table 1. Different hybrid firefly optimization algorithms.

Author's	Hybrid Firefly Model	Case Study
Zervoudakis et al. (2020) [12]	Firefly and Genetic Algorithm	Product Line Design Problem
Abdullah et al. (2012) [13]	Firefly-Differential Evolution (HEFA)	Complex and Nonlinear Problems
Tahershamsi et al. (2014) [14]	Firefly-Harmoni Search	Optimization of Water Distribution Systems
Gu et al. (2013) [15]	Firefly and Harmony Search	Global Numerical Optimization
Kora and Krishna (2016) [16]	Firefly and Particle Swarm Optimization	Detection of Bundle Branch Block
Elkhechafi et al. (2017) [17]	Firefly- Genetic Algorithm	Global Optimization
Aydilek (2018) [18]	Firefly-Particle Swarm Optimization	Computationally Expensive Numerical Problems
Nhu et al. (2020) [19]	Firefly-Particle Swarm Optimization	Rainfall induced Flash Floods
Khan et al. (2020) [20]	Firefly-Particle Swarm Optimization	Standard IEEE 30-Bus Test System
Yadav et al. (2021) [21]	Firefly and Biogeography-Base Optimization	Software Production Line
Wahid and Ghazali (2021) [22]	Firefly and Genetic Algorithm	Minimization and Maximization Functions
Bilal and Millie Pant (2020) [23]	Firefly and Particle Swarm Optimization	Optimization of Water Distribution Systems

2. Materials and Methods

2.1. Formulation of Pipe Networks Optimization

The problem of pipe network optimization is to find the best combination of pipe diameters among a set of commercially available diameters as discrete decision variables that

provides the least construction cost for the network satisfying prescribed constraints. The problem can be formulated as reported in Ezzeldin and Djebedjian [24] by the minimization of the objective function f satisfying both design constraint and hydraulic constraints, continuity and energy, as follow;

2.1.1. Total Pipe Cost

The total pipe cost of the network can be expressed by:

$$C_T = \sum_{i=1}^{N_{pipes}} c_i(D_i) * L_i \quad (1)$$

where C_T is the total construction cost of the network, N_{pipes} is the number of pipes, $c_i(D_i)$ is the cost of pipe i of discrete diameter D_i per unit length, and L_i is the length of pipe i .

2.1.2. Objective Function

The objective function of cost minimization is:

$$\text{Minimize } f = \begin{cases} C_T & \text{if } H_{j,min} - H_j \leq 0 \\ C_T + C_p & \text{else} \end{cases} \quad (2)$$

where C_p is the penalty cost = $P_C \sum_{j=1}^{N_{nodes}} (H_{j,min} - H_j)$, P_C is the penalty cost coefficient taken equal to 10,000, $H_{j,min}$ is the minimum allowable head at node j , H_j is the head at node j and N_{nodes} is the number of nodes in the pipe network.

2.1.3. Hydraulic Constraints

Continuity constraint;

$$\sum_{j=1}^{N_{nodes}} Q_j = 0, \quad (3)$$

Q_j is the discharge at node j .

Energy constraint;

$$\sum h_f = E_p, \quad (4)$$

h_f is head loss due to friction in pipe calculated using Hazen–Williams formula given by $h_f = \frac{10,674 * L_i * Q_i^{1.852}}{C_i^{1.852} * D_i^{4.87}}$; C_i is the Hazen–Williams Coefficient, Q_i is the discharge in pipe i and E_p is the energy supplied by a pump.

Design constraint;

$$D_{min} \leq D_i \leq D_{max} \quad i = 1 \dots N_{pipes}, \quad (5)$$

D_{min} , D_{max} are the minimum and maximum commercially available pipe diameters, respectively.

Nodal head constraint;

$$H_j \geq H_{j,min} \quad j = 1 \dots N_{nodes}, \quad (6)$$

A MATLAB code is developed to execute the hydraulic simulation model given by Equations (3) through (6) and an optimization code written in MATLAB is used to solve the optimization model. Both simulation and optimization models are linked to solving the simulation–optimization model.

2.2. Benchmark Networks

Three benchmark networks are considered in this study, namely, two-loop (Alperovits and Shamir [25]) with an optimal solution of 419,000 cost units, Hanoi (Fujiwara and Khang [26]) with an optimal solution of 6081×10^6 \$, and New York water supply system (Schaake and Lai [27]) with optimal solution of 38,637,600\$. The first network is the hypothetical two-loop network shown in Figure 1, which consists of 8 pipes of 1000 m

constant length and 7 nodes all fed by gravity from a single reservoir 210 m fixed elevation. Each pipe in the network is selected among 14 available discrete pipe diameters of 1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, and 24 inches with arbitrary unit costs of 2, 5, 8, 11, 16, 23, 32, 50, 60, 90, 130, 170, 300 and 550, respectively. The minimum allowable nodal head is 30 m, and the Hazen–Williams Coefficient is 130 for all pipes—the optimization algorithm searches for the optimal solution in 14^8 possible solutions for the network design.

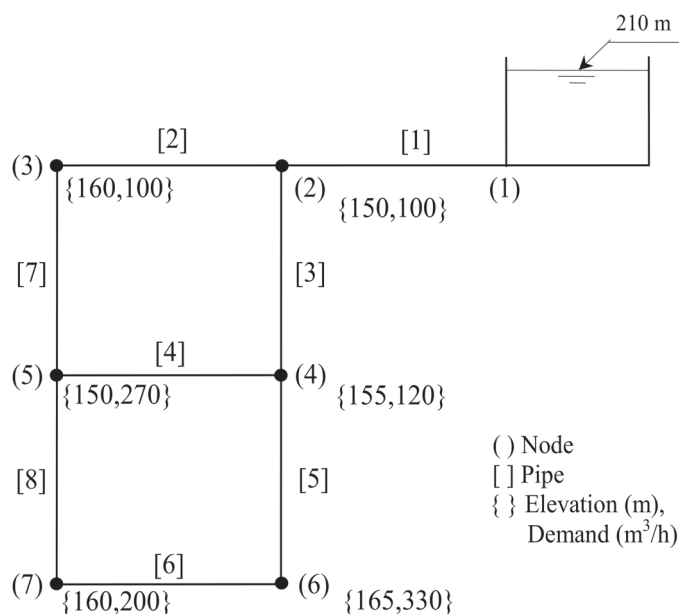


Figure 1. Two-loop network.

The second network is the Hanoi City network, Vietnam, shown in Figure 2, which is a three-loop network consisting of 34 links joined at 32 nodes and fed by gravity from a constant head reservoir of 100 m in elevation. The design of the network is restricted to selecting 6 discrete commercially available pipe sizes of 12, 16, 20, 24, 30, and 40 inches of, which cost 45.73, 70.4, 98.38, 129.3, 180.8 and 278.3 \$/m, respectively. The minimum head at each node is required to be greater or equal to 30 m. above ground level, with the Hazen–Williams coefficient being 130 for all pipes. The optimal design of the network is searched among 6^{34} possible network designs.

The third network is the New York City water supply system, for which the layout is shown in Figure 3. The network is fed from the single source Hillview Reservoir at a constant level of 300 ft and comprises 21 pipes and 20 nodes arranged in two loops. As a result of the growing demands at certain nodes 16, 17, 18, 19, and 20 in the existing network, it was required that the network be rehabilitated in order to increase the prespecified nodal pressures to meet the new conditions. A parallel expansion has been proposed by constructing new gravity tunnels parallel to the existing ones to increase the heads at nodes 16, 17, and 18 to 260, 272.8, and 272.8 and 255 ft., respectively, while maintaining a head of 255 ft. at other nodes. The solution space has 16^{21} possible designs with a Hazen–Williams roughness coefficient of 100. The available pipe diameters are in inches and cost \$/ft. are 0(0), 36(93.5), 48(134), 60(176), 72(221), 84(267), 96(316), 108(365), 120(417), 132(469), 144(522), 156(577), 168(632), 180(689), 192(746), and 204(804).

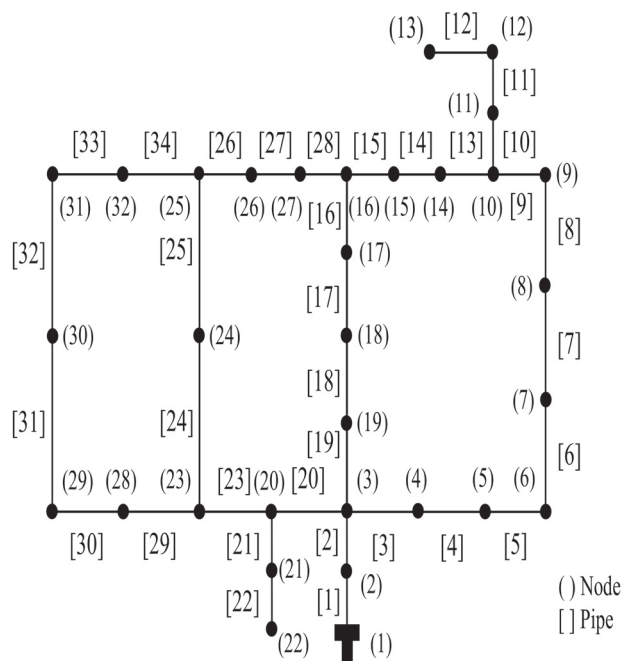


Figure 2. Hanoi city network, Vietnam.

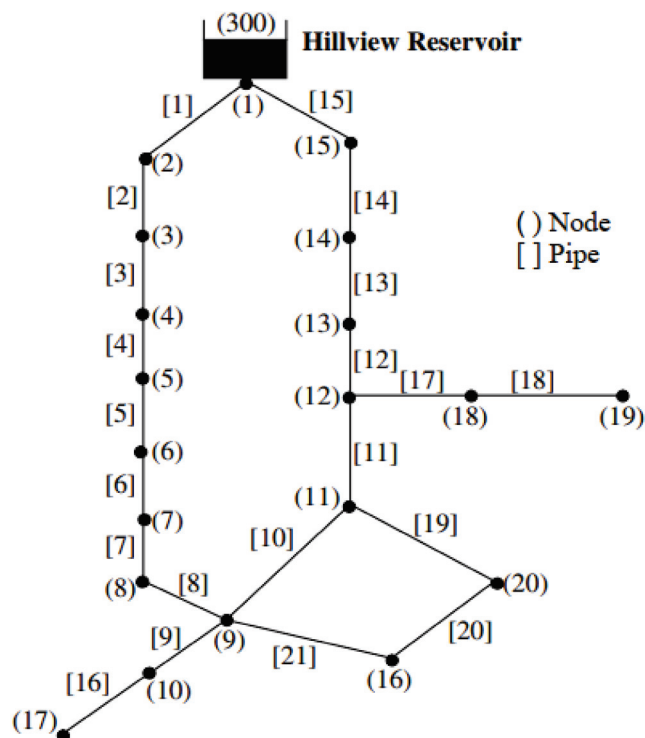


Figure 3. New York City water supply system.

For the selected benchmark networks of known optimal solutions obtained by many researchers, the optimization models are tested for reaching the known optimal solutions with better performance and search capabilities in the solution space.

2.3. Real Case Study of El-Mostakbal City Network

The models are also applied to the real case study of the El-Mostakbal city network shown in Figure 4, which has been constructed as an extension to the Ismailia city network in Egypt (Rayan et al. [28]). The network is of the unknown optimal solution for which the

models are applied and tested to be able to reach a new optimal solution better than that of 4,926,560.7 LE using the modified Jaya algorithm (Abdel-Gawad [29]). As a real large-scale network that has a huge solution space of 10^{44} possible solutions, the El-Mostakbal city network is recommended to be used for testing the search capability and performance of the different optimization algorithms (Abdel-Gawad [29]). The network has 44 pipes and 33 nodes. The available pipe sizes are 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0 and 1.2 m. at the cost of 188, 255, 333, 419, 570, 735, 1110, 1485, 2505 and 3220 LE/m., respectively. The network is designed to satisfy a minimum required head of 22 m at all nodes with Hazen–Williams coefficient of 22 m for all pipes. The network has previously been analyzed by many researchers using different optimization techniques, including Rayan et al. [28], El-Ghandour and Elbeltagi [30], Ezzeldin and Djebedjian [24] and Abdel-Gawad [29].

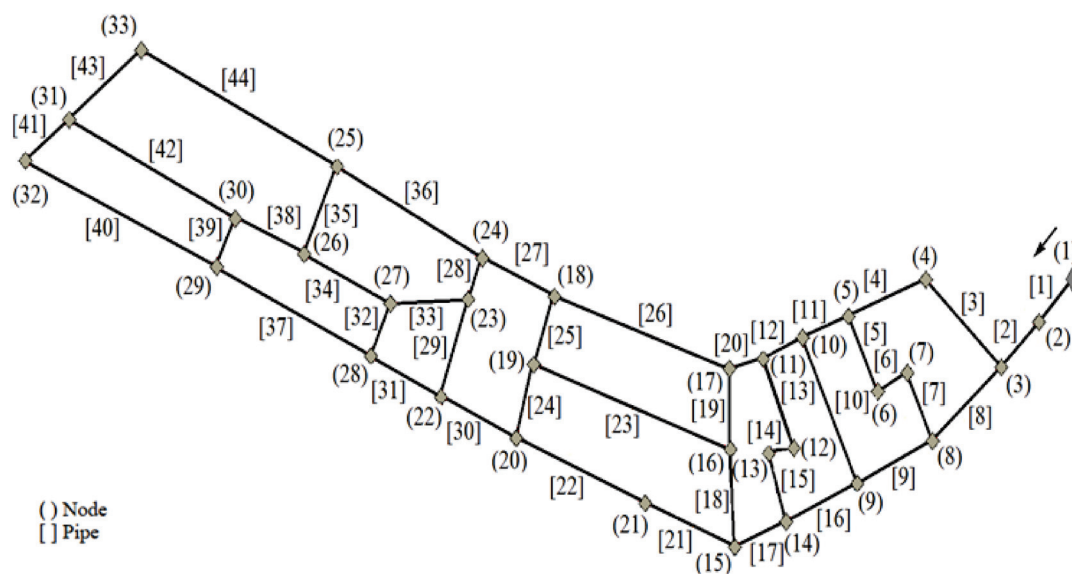


Figure 4. El-Mostakbal city network, Ismailia, Egypt [28].

3. Firefly Optimization Algorithm

The firefly optimization algorithm first introduced by Yang [31] is a swarm intelligence population-based metaheuristic optimization technique inspired by the natural behavior of fireflies and can be used to solve both continuous and discrete optimization problems [12]. The algorithm proved to be an efficient search method for non-linear optimization problems and, when compared to PSO and GA for finding the global optima of various test functions, showed superiority in terms of efficiency and success rate [31]. However, the algorithm could fall into a locally optimal solution or suffer from low accuracy when solving high-dimensional optimization problems [32]. The algorithm has been applied to many problems related to water resources engineering [33–36]. Up to the knowledge of the authors, the firefly algorithm has not yet been applied for the least cost design of water distribution systems.

3.1. Formulation of Firefly Algorithm (FA)

Firefly algorithm, FA is based on the following three rules, (1) all fireflies are unisex, (2) attractiveness is proportional to their brightness, and (3) the brightness of a firefly is determined by the landscape of the objective function.

A detailed formulation of the firefly algorithm, as found in Yarpiz [37], can be summarized as follow:

1. Initialize the input parameters for FA.
2. Generate an initial population of n_{pop} fireflies for the dimension of N_{pipes} .
3. The total construction cost of the network, C_T and the corresponding constraint for each firefly is evaluated using the simulation model.

4. The fitness of each firefly, f_i , $i = 1, 2, 3, \dots, n_{pop}$ (the summation of total construction cost and penalty due to the constraints violation [Equation (2)]) is computed.
5. Compare the fitnesses f_i and f_j for each of the two fireflies i and j , respectively, (i and $j = 1: n_{pop}$ and $i \neq j$).
6. If $f_i > f_j$, firefly i moves towards firefly j . Update the position of firefly i , $X_i(t)$ according to Equation (7) and calculate its fitness f'_i at the new position, $X_i(t + 1)$.

$$X_i(t + 1) = X_i(t) + \beta \cdot r_n (X_i(t) - X_j(t)) + \alpha_1(t) \Delta R_n \quad (7)$$

where $\beta = \beta_0 e^{-\gamma r_{ij}^2}$ is the attractiveness, β_0 = coefficient base value at $r = 0$, γ = light absorption coefficient and $r_{i,j}$ calculated as:

$$r_{ij} = d_{ij} / d_{max} \quad (8)$$

where d_{ij} is the distance between any two fireflies i and j which can be determined by the cartesian distance in the form:

$$d_{ij} = \sqrt{\sum_{k=1}^{N_{pipes}} (X_{i,k} - X_{j,k})^2}$$

and

$$d_{max} = \sqrt{\sum_{k=1}^{N_{pipes}} (D_{max_k} - D_{min_k})^2}$$

$X_{i,k}$ is the k^{th} component of the spatial coordinate X_i of i^{th} firefly, D_{min} and D_{max} are vectors of the minimum and maximum allowable diameters, r_n is a vector with uniformly distributed random numbers, $\Delta = 0.05 (D_{max} - D_{min})$ is the uniform mutation range, R_n is a vector with continuous uniform distribution with the lower endpoints-1 and upper endpoint 1 and $\alpha_1(t) = \alpha_0 d_r^{t-1}$ is the mutation coefficient at iteration t in which α_0 = initial mutation coefficient and d_r is the mutation coefficient damping ratio

7. If $f'_i < f_i$ replace the position of the firefly i , $X_i(t)$ with the updated one, $X_i(t + 1)$ otherwise keep the old position of the firefly i .
8. Repeat Steps 5 to 7 until the maximum number of iterations, n_{iter} is reached.
9. Rank the fireflies and find the current best solution.

3.2. Hybrid Firefly-Particle Swarm Optimization (FAPSO) Model

Aydilec [18] Combined the search ability of firefly FA and particle swarm PSO optimization algorithms through hybrid firefly and particle swarm optimization model which used the ability of PSO to provide fast convergence in exploration (local optima) in the global search while FA is generally used in local search due to its ability in fine-tuning in exploitation (global optima). The model can be summarized in the following steps:

1. Initialize the input parameters of the FA and PSO algorithms.
2. Generate an initial population of n_{pop} particles with random positions and velocity on N_{pipes} dimensions in the solution space.
3. Calculate the fitness, f_i for each particle, i in the population ($i = 1, 2, 3, \dots, n_{pop}$)
4. Select the social global best, $gbest$ and personal best, $pbest$ particles.
5. Compare each particle's fitness f_i value in the population with $gbest$ in the last iteration ($t - 2$). If $f_i < gbest(t - 2)$ ($t > 2$, t indicates the iteration number) start local search using FA as given in Equations (9) and (10)

$$X_i(t + 1) = X_i(t) + \beta (X_i(t) - gbest(t - 2)) + \alpha \left(r_n - \frac{1}{2} \right) \quad (9)$$

$$V_i(t + 1) = X_i(t + 1) - X_i(t)$$

$$\text{the attractiveness } \beta = \beta_0 e^{-\gamma r_{ij}^2} \text{ in which } r_{ij} = db_{ij} / d_{max} \quad (10)$$

where db_{ij} is calculated as:

$$db_{ij} = \sqrt{\sum_{k=1}^{N_{pipes}} (X_{i,k}(t) - gbest_k(t-2))^2}$$

Otherwise, the particle will be handled by *PSO*. The velocity, V_i and position, X_i of the i^{th} particles are given by Equations (11) and (12) as:

$$V_{i,k}(t+1) = wV_{i,k}(t) + c_1r_1(pbest_{i,k}(t) - X_{i,k}(t)) + c_2r_2(gbest_k(t) - X_{i,k}(t))$$

$$V_{max} > V_{i,k}(t+1) > V_{min} \quad (11)$$

$$X_i(t+1) = X_i(t) + V_i(t+1) \quad (12)$$

where $V_i(t+1)$ is the particle velocity in iteration $(t+1)$, $w = 0.90 - t(\frac{0.40}{n_{iter}})$ is the inertia weight. r_1 and r_2 are random numbers in range of $[0,1]$. c_1 and c_2 are the acceleration coefficient, and V_{max} is the maximum change of the particle velocity.

6. Compare fitness, f_i for each particle, i in the population with those of $gbest$ and $pbest$ particles. Update $gbest$ for the population and $pbest$ of every particle.
7. Repeat steps 5 to 6 until the maximum number of iterations, n_{iter} is reached.

3.3. Hybrid Firefly-Genetic Algorithm Model (FAGA)

Zervoudakis et al. [12] proposed a hybrid approach (*FAGA*) based on the firefly algorithm, *FA* and the genetic algorithm, *GA*, to combine the advantages of both algorithms for which the procedure is summarized as follows:

1. Generate a random initial population of n_{pop} fireflies.
2. Calculate the fitness, f_i for each firefly, i in the population ($i=1, 2, 3, \dots, n_{pop}$)
3. Compare the fitness f_i and f_j for each of the two fireflies i, j , respectively, (i and $j = 1: n_{pop}$ and $i \neq j$).
4. Apply genetic crossover for the two fireflies i and j for the case $f_j < f_i$ according to Equations (13) and (14).

$$X_i(t+1) = L * X_i(t) + (1 - L) * X_j(t) \quad (13)$$

$$X_j(t+1) = L * X_j(t) + (1 - L) * X_i(t) \quad (14)$$

L is a vector with continuous uniform distribution with the lower endpoints 0 and upper endpoint $(1 + r)$ where r is a single uniformly distributed random number in the interval $(0,1)$.

$L * X_i(t)$ multiplies arrays L and $X_i(t)$ by multiplying corresponding elements.

On the contrary, if $f_j > f_i$, apply the genetic mutation in both fireflies as given in Equations (15) and (16).

$$X_{i,k}(t+1) = X_{i,k}(t) + \text{sigma}(k) * R \quad (15)$$

$$X_{j,k}(t+1) = X_{j,k}(t) + \text{sigma}(k) * R \quad (16)$$

where $\text{sigma} = 0.10 (D_{max} - D_{min})$, k is a vector with n values; $n = (mu * N_{pipes})$ and mu is the mutation coefficient which are sampled uniformly at random without replacement,

from the integers 1 to n_{pipes} , and R is a vector of random n values drawn from the standard normal distribution.

5. Replace the old solutions for the fireflies i and j with the new ones if they have better fitnesses.
6. Repeat steps 3 to 5 until reaching the maximum number of iterations, n_{iter} .

3.4. Models Parameters

Setting the values of the parameters for each algorithm is a crucial issue in the optimization process to reach an optimal solution for each of the four tested networks. Several trial runs were carried out for each algorithm to select the most appropriate values of its related parameters. Table 2 shows the final values of the parameters for each algorithm.

Table 2. Values of the parameters for the models *FA*, *FAPSO* and *FAGA*.

Model	Parameter	Pipe Network			
		Two-Loop	Hanoi	New York	El-Mostakbal
FA	n_{iter}	1000	1000	1000	1000
	n_{pop}	10	40	40	40
	Γ	1	1	1	1
	β_0	2	2	2	2
	α_0	0.2	0.2	0.2	0.2
FAPSO	n_{iter}	130	150	200	150
	n_{pop}	70	350	200	400
	c_1	1	1.49	1.49	1.49
	c_2	1.1	1.49	1.1	1.49
	Γ	1	1	1	1
	β_0	2	2	2	2
	A	0.2	0.2	0.2	0.2
FAGA	n_{iter}	1000	1000	1000	1000
	n_{pop}	10	40	40	40
	Mu	0.15	0.15	0.1	0.2

4. Application and Results

The optimal solutions for the El-Mostakbal city water distribution network obtained using different optimization algorithms available in the literature are listed in Table 3, showing that the hybrid model *FAGA* introduced in the present study succeeded in reaching a new optimal solution of 4,923,731.5 L.E. compared to the last available optimal solution of 4,926,560.7 obtained by Abdel-Gawad [29] using the modified Jaya algorithm. The optimal diameters of the network are shown in Table 4.

Table 3. Optimal cost for El-Mostakbal city network using different optimization algorithms.

Author's	Optimization Technique	Optimal Cost
Rayan et al. (2003) [28]	SUMT	6,770,787
	GA	5,268,431
	PSO	4,968,881.5
El-Ghandour and El-Beltagi (2018) [30]	ACO	5,484,596
	MA	5,055,519
	SFLA	5,181,846
Ezzeldin and Djebedjian (2020) [24]	WOA	4,932,467.1
Abdel-Gawad (2021) [29]	FSAJA	4,926,560.7
	FA	5,676,331.79
Present Study	FAPSO	4,932,901
	FAGA	4,923,731.5

Note(s): SUMT (Sequential Unconstrained Minimization Technique), GA (Genetic Algorithm), PSO (Particle Swarm Optimization), ACO (Ant Colony Optimization), MA (Memetic Algorithm), WOA (Whale Optimization Algorithm), FSAJA (Free Sensitivity Analysis Jaya Algorithm), FA (Firefly Algorithm), FAPSO (Hybrid Firefly-Particle Swarm Optimization), FAGA (Hybrid Firefly-Genetic Algorithm).

Table 4. Optimal pipe diameters of El-Mostakbal city network.

Pipe Number (Optimal Diameter, mm.)					
1 (600)	2 (500)	3 (500)	4 (500)	5 (150)	6 (150)
7 (150)	8 (150)	9 (150)	10 (150)	11 (500)	12 (500)
13 (150)	14 (150)	15 (150)	16 (150)	17 (150)	18 (150)
19 (150)	20 (500)	21 (150)	22 (150)	23 (150)	24 (150)
25 (150)	26 (400)	27 (400)	28 (250)	29 (150)	30 (150)
31 (150)	32 (150)	33 (200)	34 (150)	35 (250)	36 (300)
37 (150)	38 (250)	39 (250)	40 (200)	41 (150)	42 (150)
43 (150)	44 (200)				

Performance Evaluation

The performance of the three optimization models applied to the networks considered in the study was assessed according to two stages. The first stage includes a set of different measures, namely, (1) minimum cost, maximum cost, mean and standard deviation columns 1, 2, 3, and 4), respectively; (2) convergence criteria measured by the function evaluation number and the computational time required for performing 1000 evaluations (columns 5 and 6), respectively. The results of the first stage of assessment are shown in Table 5, which clearly illustrates that the FAGA hybrid model has the best values for the minimum and maximum cost, the mean and standard deviation for all networks, which means better search capability in the huge search space (14^8 , 6^{34} , 10^{44} and 16^{21} for the two-loop, Hanoi, El-Mostakbal and New York networks, respectively). Besides, the values of the number of function evaluations and the computing time for 1000 evaluations are the lowest for all networks compared to FA and FAPSO, which means faster convergence of the hybrid FAGA model towards the optimal global solution. The case study of El-Mostakbal city network optimized by firefly algorithm and the two hybrid models, FAPSO and FAGA is shown in Figure 5 which clearly illustrates the faster convergence of the FAGA model in reaching an optimal solution of 4,923,731.5 LE. at a number of function evaluations of 37,440 compared to 5,966,072.39 L.E. and 4,964,187.63 L.E. for FA and FAPSO, respectively at the same number of function evaluations.

Table 5. Performance evaluation according to the first stage of assessment.

Network	Optimization Algorithm	(1)	(2)	(3)	(4)	(5)	(6)
		Min. Cost	Max. Cost	Mean	Standard. Deviation	F.E.N.	Sec Per 1000 Eval
Two-Loop	FA	419,000	441,000	425,150	8317.86	6205	88.8
	FAPSO	419,000	453,000	435,700	11,388.36	2596	85.3
	FAGA	419,000	420,000	419,160	370.33	2380	82
Hanoi	FA	6,566,082.81	8,307,245.89	7,402,370.25	524,647.62	52,249	91.8
	FAPSO	6,195,529.34	69,044,904.1	6,507,346.32	208,328.43	102,960	88.3
	FAGA	6,087,729.57	6,375,686.7	6,252,830.16	79,998.3	37,410	82
New York	FA	38,637,600	62,390,579.7	44,093,383.99	5,396,845.17	22,335	91
	FAPSO	38,637,600	61,551,400	40,393,718.25	5,139,391.02	13,916	89.2
	FAGA	38,637,600	38,796,300	38,662,992	58,771.06	9120	88.1
El-Mostakbal	FA	5,676,331.79	6,263,583.1	5,913,233.06	170,902.64	55,216	94.3
	FAPSO	4,932,901	5,214,838	5,046,771.6	92,426.21	58,842	90.5
	FAGA	4,923,731.5	5,025,247.3	4,949,974.37	35,382.66	37,440	88

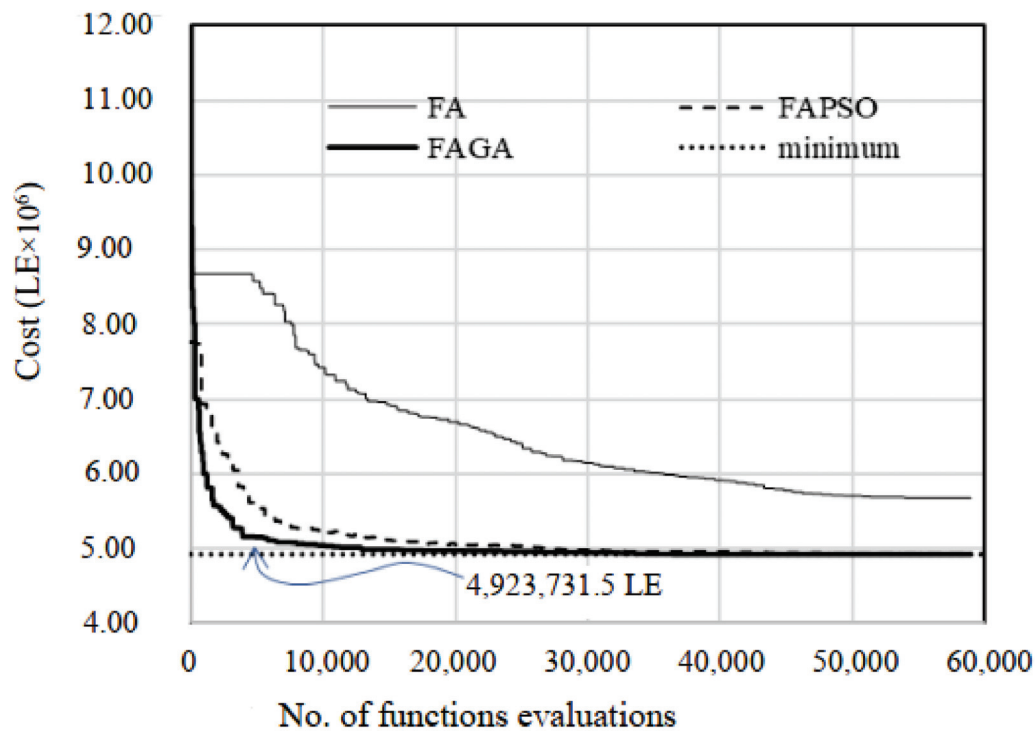


Figure 5. Convolution of the cost with the number of functions evaluations for El-Mostakbal city network.

In the second stage of performance evaluation, the performance of the firefly algorithm and the two hybrid models, FAPSO and FAGA, is assessed using the success rate, Sr , estimated by the fuzzy logic concept. The success rate has been first introduced by Mora-Melia et al. [38] as a measure of the quality and convergence of an optimization algorithm. Quality refers to the ability of an algorithm to obtain the maximum number of good solutions as a ratio to the total number of simulations performed. In the present study, the success rate is utilized as a measure of an algorithm to obtain the maximum number of good solutions (near-optimal solutions) for the prespecified total number of simulations. An optimization error C is defined as the limit of exceedance of the good solution beyond the optimal solution of the network. Values of C considered in this study were 0, 0.01 and 0.02. The success rate is then evaluated using the fuzzy logic concept first introduced by Cullinane et al. [39] and later used by El-Ghandour et al. [40] to determine the nodal hydraulic availability indices. The following steps describe the procedure of the fuzzy logic method:

1. Determine the known optimal solution $f(x^*)$ for the pipe networks (two-loop, 419,000, Hanoi, 6.081×10^6 and New York, 38,637,600). If the known optimal solution is not available, $f(x^*)$ is replaced with the best-known optimal solution (El-Mostakbal, 4,923,731.5 obtained from the present study).
2. The robustness of the optimization algorithm is measured by accepting optimal solutions $f(x)_{max}$ slightly greater than the known optimal solution $f(x^*)$ such that $f(x)_{max} = (1 + C) * f(x^*)$ where $C = 0, 0.01$ and 0.02 .
3. Run each of the three optimization algorithms considered in this study, FA, FAPSO and FAGA, 20 times for each of the four networks and denote the objective function at the termination point, $f(x_{opt})_i$, $i = 1, 2, 3, \dots, 20$.
4. Estimate the Acceptance Index AI_i as given in Equation (17) using the principles of fuzzy logic [39]. Values of optimization error, $C = 0, 0.01$, and 0.02 , are assumed to be acceptable. Zero value of C means a tenuous relationship between AI_i and $f(x_{opt})_i$. At the same time, the second and third values of C denote continuous function (S-shape fuzzy membership function) to simulate the relationship between the Acceptance index, AI_i and $f(x_{opt})_i$. As given in Equation (17), it is clear that

AI_i takes a value equal to 1 if $f(x_{opt})_i = f(x^*)$ and value between 1 and zero if $(1 + C) * f(x^*) > f(x_{opt})_i > f(x^*)$ while it takes value of zero if $f(x_{opt})_i$ more than or equal $(1 + C) * f(x^*)$.

$$AI_i = \begin{cases} 0 & \text{if } f(x_{opt})_i > f(x_{max}) \\ 2 \left\{ \frac{f(x_{opt})_i - (1+C) \times f(x^*)}{C \times f(x^*)} \right\}^2 & \text{if } \left(1 + \frac{C}{2}\right) \times f(x^*) < f(x_{opt})_i < (1 + C) \times f(x^*) \\ 1 - 2 \left\{ \frac{f(x_{opt})_i - f(x^*)}{C \times f(x^*)} \right\}^2 & \text{if } f(x^*) < f(x_{opt})_i < \left(1 + \frac{C}{2}\right) \times f(x^*) \\ 1 & \text{if } f(x_{opt})_i = f(x^*) \end{cases} \quad (17)$$

Estimate the success rate Sr as:

$$Sr = 100 * \sum_{i=1}^{20} AI_i / 20 \quad (18)$$

The results of the success rate obtained using the proposed algorithms for the different networks are shown in Table 6 which clearly illustrates the effectiveness and quality of the FAGA hybrid model as the values of the success rate are remarkably higher than the corresponding values for the traditional FA and hybrid FAPSO models for all networks especially EL-Mostakbal network considering the prespecified limits of the optimization error C .

Table 6. Success rates using the proposed optimization algorithms.

Network	Optimization Algorithm	Success Rate (Sr %)		
		$C = 0$	$C = 0.01$	$C = 0.02$
Two-loop	FA	25	56.01	60.65
	FAPSO	15	15	16.69
	FAGA	84	98.18	99.54
Hanoi	FA	0	0	0
	FAPSO	0	0	0.1314
	FAGA	2	7.5	10.73
New York	FA	5	8.31	13.03
	FAPSO	5	5	5
	FAGA	84	94.6	98.65
El-Mostakbal	FA	0	0	0
	FAPSO	0	11.39	29.31
	FAGA	40 *	66.89	77.1

Estimation of the acceptance index AI (Equation (17)) is based mainly on obtaining an optimal solution $f(x_{opt})_i$ greater than the known optimal solution of the network by a value of optimization error $C = 0, 0.01$, and 0.02 . For $C = 0$, only the runs providing optimal solutions $f(x^*)$ are accepted and take the value of $AI = 1$, while $C = 0.01$ and 0.02 only runs giving optimal solutions equal or greater than the optimal solution by about C take values of $AI = (0,1)$. Figure 6 shows the continuous function (S-shape fuzzy logic) for the relationship between acceptance index and cost ratio $f(x_{opt})_i / f(x^*)$. Table 7 illustrates the procedure of calculating the success rate Sr (Equation (18)) for the El-Mostakbal city network by performing 20 runs and considering the different values of C . The values of the acceptance index AI of FAGA for the El-Mostakbal city network (twenty runs—different values of optimization error C) are given in Table 7. The values of Sr are also calculated and given in the table.

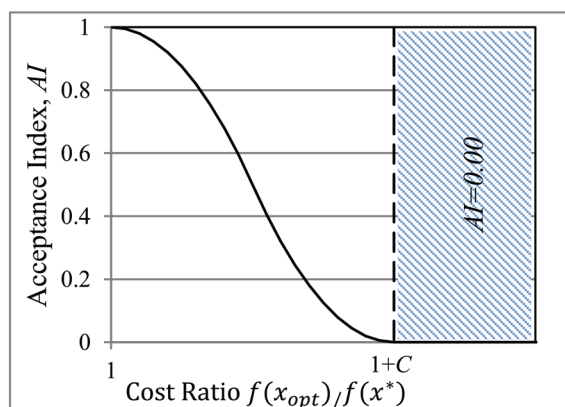


Figure 6. S-shape fuzzy logic relationship of acceptance index and cost ratio.

Table 7. Estimation of success rate (S_r %) of FAGA optimization model for El-Mostakbal City network.

Run No.	Acceptance Index (AI)			Run No.	Acceptance Index (AI)		
	$C = 0.00$	$C = 0.01$	$C = 0.02$		$C = 0.00$	$C = 0.01$	$C = 0.02$
1	1	1	1	11	0	0.687	0.922
2	1	1	1	12	0	0.687	0.922
3	1	1	1	13	0	0.687	0.922
4	1	1	1	14	0	0.687	0.922
5	1	1	1	15	0	0.687	0.922
6	1	1	1	16	0	0.247	0.790
7	1	1	1	17	0	0	0.091
8	1	1	1	18	0	0	0.004
9	0	0.879	0.970	19	0	0	0.002
10	0	0.819	0.955	20	0	0	0
* $S_r = (13.38/20) \times 100 = 40\%$.				Σ	8.00	13.38	15.42
				S_r %	40.0 *	66.90	77.10

5. Conclusions

The present research introduced two hybrid models, firefly-particle swarm optimization (FAPSO) and firefly-genetic algorithm (FAGA), to enhance the performance of the standard firefly algorithm (FA). The proposed models were tested through application to the three well-known benchmark networks of known optimal solutions, namely, two-loop, Hanoi and New York, and also to the real large-scale case study of El-Mostakbal city network, Egypt, of the unknown optimal solution obtained yet. The results revealed that the proposed FAGA model was able to reach the known optimal solutions of 419,000 cost units, 6.081×10^6 \$ and 38,637,600 \$ for the benchmark networks, respectively. For the real case study of the El-Mostakbal city network, the FAGA model succeeded in reaching a new optimal solution of 4,923,731.5 L.E. compared to the last optimal cost of 4,926,560.7 L.E. available in the literature. Additionally, performance evaluation of the proposed algorithms in terms of function evaluation number, computational time, selected related cost measures, namely, minimum, maximum, mean and standard deviation and finally, success rate, revealed that FAGA, when compared to the standard FA and the hybrid model FAPSO had a better search capability in huge solution spaces, faster convergence towards an optimal solution, balancing between exploration and exploitation phases, the higher capability of finding the optimal solution. Finally, it can be concluded that the FAGA hybrid optimization algorithm is a very promising optimization tool and has an attractive

ability to efficiently handle pipe network optimization problems. For future studies, it is recommended that the model be applied to multi-objective pipe network optimization.

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Article

Experimental and Numerical Study on Flow Control Using 3-Array Submerged Vane in Laboratory Channel Bend

Bestami Taşar ¹, Fatih Üneş ¹, Ercan Gemici ² and Martina Zelenakova ^{3,*}

¹ Department of Civil Engineering, Iskenderun Technical University, Iskenderun 31200, Turkey

² Department of Civil Engineering, Bartın University, Bartın 74100, Turkey

³ Department of Environmental Engineering, Technical University of Kosice, 042 00 Kosice, Slovakia

* Correspondence: martina.zelenakova@tuke.sk

Abstract: Regulation structures such as submerged vane are needed to reduce and eliminate environmental damage due to increased flooding in rivers. In particular, scours on the outer bank due to increased flow velocities cause the river bed to change and deteriorate. In this study, the effect on flow velocities was investigated experimentally by using 3-array submerged vane structures in areas close to the outer bank. The experimental vane results were performed in the open channel setup. The Computational Fluid Dynamics (CFD) results obtained with the numerical model were also verified and compared with experimental results. It has been observed that the CFD model gives results close to the real experimental results. The standard-based $k-\epsilon$ model was used as the turbulence model. In the outer meander, the 3-array submerged vane with a 3-vane structure was found to affect the flow velocity by 16–27% in the region behind the vane. The flow velocities were investigated along with depth using the CFD and found that the mean velocity was reduced by 14–21% along the depth. It is also recommended that submerged vane structures can be applied as an effective method in reducing flow velocities and directing flows.

Keywords: submerged vane; meander; experiment; computational fluid dynamics; open channel flow

1. Introduction

Regarding, river meandering regulation and especially submerged vane studies, the complexity of the subject matter is unsteady and nonlinear due to the effect of more parameters on the event, and has been studied by very few researchers in the past. Therefore, there is very limited laboratory study. Studies conducted with a submerged vane in meander curves in the 1980s by Odgaard and Kennedy, Odgaard and Lee, Odgaard [1–4] pioneered the entry of submerged vane into the literature as a new method. Marelius and Sinha [5] conducted a study to create the optimum vane angle required to create the strongest secondary circulation in the open channel flow. Voisin and Townsend [6] investigated the optimal size of submerged vanes to protect meandering riverbanks. Gemici [7] investigated the effects of different Froude numbers, vane arrangement, vane length/vane height and approach angle combinations on flow velocity. Mohammediun et al. [8] conducted their research to reduce sedimentation and erosion potential at the junction of curved and straight channels. Fathi et al. [9] investigated the effects of submerged vanes on scrubbing around a vertical wall and overflow abutments with laboratory results. Kalathil et al. [10] used submerged vanes to control sediment entry into the inlet channel with a physical model. Zarei et al. [11] investigated the effects of submerged vanes around the bridge pier and on bed topography changes. Lake et al. [12] investigated the effect of river-based, submerged vane structures in Australia. Gumgum and Cardoso [13] investigated the effects of different vane parameters and water discharge ratios on the bed morphology around a 90° lateral water diversion. Bor [14] studied a 90° water intake to study 3D flow patterns and sediment distribution using submerged vanes. 3D velocity components were measured

using acoustic Doppler velocimetry (ADV). According to her study, downstream corner of the intake, high velocities were measured where scouring occurred.

In this study, the vane experiments were further validated by the numerical method. As a numerical approach, Computational Fluid Dynamics (CFD) was applied to the open channel flow conditions. Ansys-Fluent program containing CFD rules was used. CFD is a branch of fluid mechanics in which problems affecting fluid behavior are analyzed by solving them in 3 dimensions with numerical methods and algorithms. In complex geometries, viscosity, flow velocity, temperature differences etc. the solution is very difficult, if not often impossible, when the parameters are applied to the fundamental equations of fluid mechanics. In CFD methods, the three basic equations governing the fluid motion, continuity, momentum and energy equations are taken as a basis. These equations are solved numerically to reach the pressure, velocity etc. of the flow variables depending on these parameters [15–18]. The flow domain is divided into finite volumes in which discretized versions of the equations governing the flow are written.

When the past studies were examined, it has been determined that there were very few or limited studies to reduce/prevent scours caused by high flow velocities in the meandering of the rivers. This study focuses on the effect of the submerged vane, which is accepted as a new method [19], on the meandering open channel. In this study, experiments at the open channel laboratory were performed on the bend part with 3-array 9 submerged vane and without submerged vane. CFD models are verified by Open channel experiments without vane and 3-array with 9 submerged vanes situations. The submerged vane experiments conducted in this study will contribute to the subject by researching the originality of the river meanders and the effect of the vane. In addition, flow velocities in the open channel were modeled with the CFD method and the cross-sectional flow velocity changes were investigated along the depth.

2. Materials and Methods

The performance of without vane and 3-array with 9 submerged vanes models in meandering open channel flows has been investigated by using a flow discharge of 25 L/s in this study. Detailed information about the experimental setup, experimental conditions and mathematical model for the without-vane and with-vane experiments conducted in the open channel are given below.

2.1. Experimental Set-Up

In Bartın University Hydro-mechanic Laboratory, a 30 cm wide curvilinear channel was built within a 50 cm wide rectangular channel within the existing open channel system. Flow condition details for the experiment are given in Table 1. Q , B , d , A , T , R_h , Fr and V_{mean} denote the discharge flow, channel width, depth of flow, wetted area, wetted perimeter, hydraulic radius, flow Froude number and inlet mean flow velocity in Table 1. In this study, since the Froude number is less than 1, it was observed that there is a subcritical flow or river regime.

Table 1. The Flow conditions for the submerged vane experiment.

Q ($\text{m}^3 \text{s}^{-1}$)	B (m)	d (m)	A (m^2)	T (m)	R_h (m)	V_{mean} (m s^{-1}) (m s^{-1})	Fr
0.025	0.300	0.095	0.0285	0.490	0.058	0.900	0.94

In order for the flow to occur in river conditions, the bottom of the channel was laid with 15 cm of sediment (gravel) material and the base of the vane was placed on the sand of 5 cm. The experimental conditions prepared for the “with vanes” situation was also provided for the without vane situation. With the start of the pump, the water drawn from the main reservoir passes through the gravel filters and reaches the rectangular channel. With the ultrasonic flow meter, the flow discharge given to the channel through the pipe

was determined. For the desired test set, the flow discharge is fixed by adjusting the vane. It was waited for 10–15 min for the flow conditions to stabilize. Flow discharge adjustments were made with an ultrasonic flow meter (Figure 1c). When the measurements were completed, the base of the channel was corrected, and a new setup was created for the other set. Details of 9 submerged vane experiments with 3 arrays were given in Figure 1a.

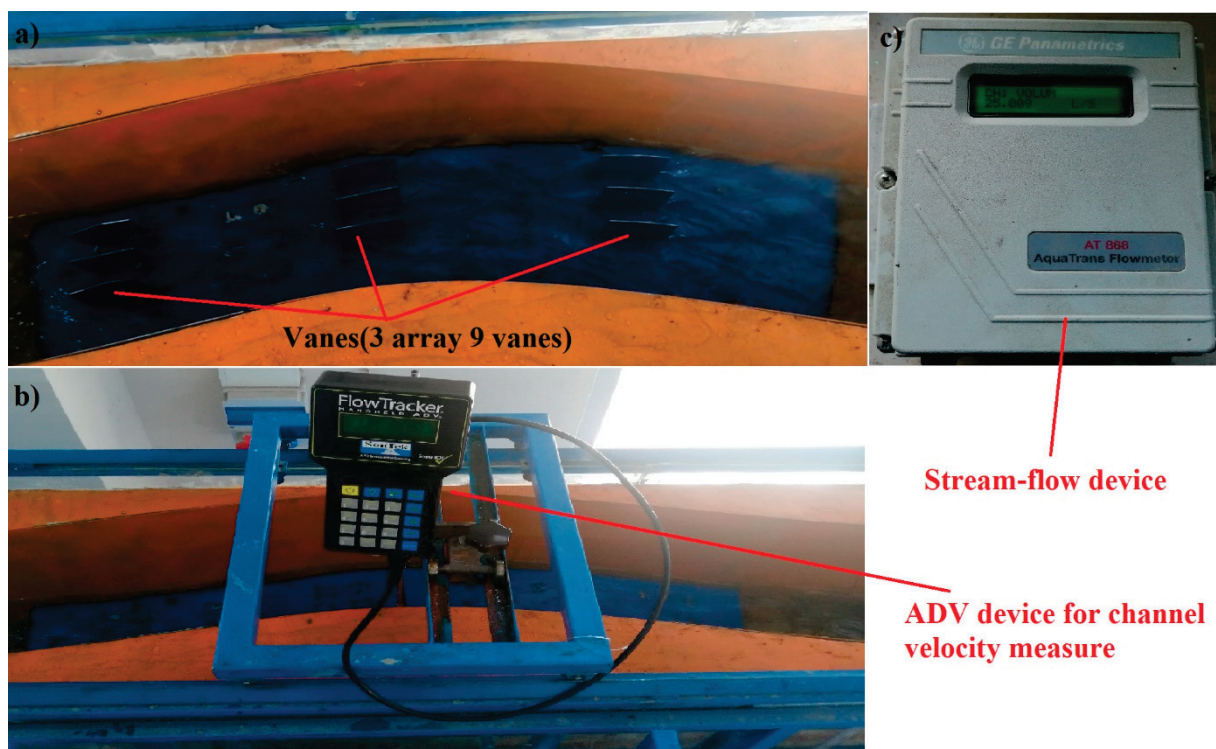


Figure 1. Experimental details for submerged vane (a) “with vane” situation (b) ADV device for velocity determination (c) Flowmeter for channel flow.

The flow discharges were measured by an Acoustic Doppler Velocimetry (ADV) flowmeter (Figure 1b). Measurements were made at 60% (0.6 d) of the depth. The working principle of the velocity meter is that the 2 acoustic receivers at the end determine the flow velocity by sending a signal.

In order to reduce the turbulence of the flow entering the channel, the energy of the water was reduced by taking the water entering with the pump into the settling tank. The open channel assembly in which the submerged vane experiment was performed had a base slope of 0.0003. A meandering channel, approximately 3 m long and 30 cm wide, was constructed along the 50×50 sectioned rectangular channel. A curved 30° channel bend connects to the upstream and downstream channels. The center radius of the curvature is $R = 3.60$ m. The vane is made of sheet metal with a thickness of 2 mm. On the bottom of the submerged vane, a 5 mm thick sheet of material was mounted in accordance with the slope/dimensions of the meandering channel and was removed and installed during each experiment. These dimensions have also been considered in the numerical simulations. The experimental setup and sectional information were shown in Figure 2.

The submerged vane experimental setup is given in the above Figure 3. for the “with vane” case. The design for submerged vane experiments, 3D flow velocity modeling and analysis of the experimental results will be emphasized. The presented submerged vane and previously experimental details were given in Table 2.

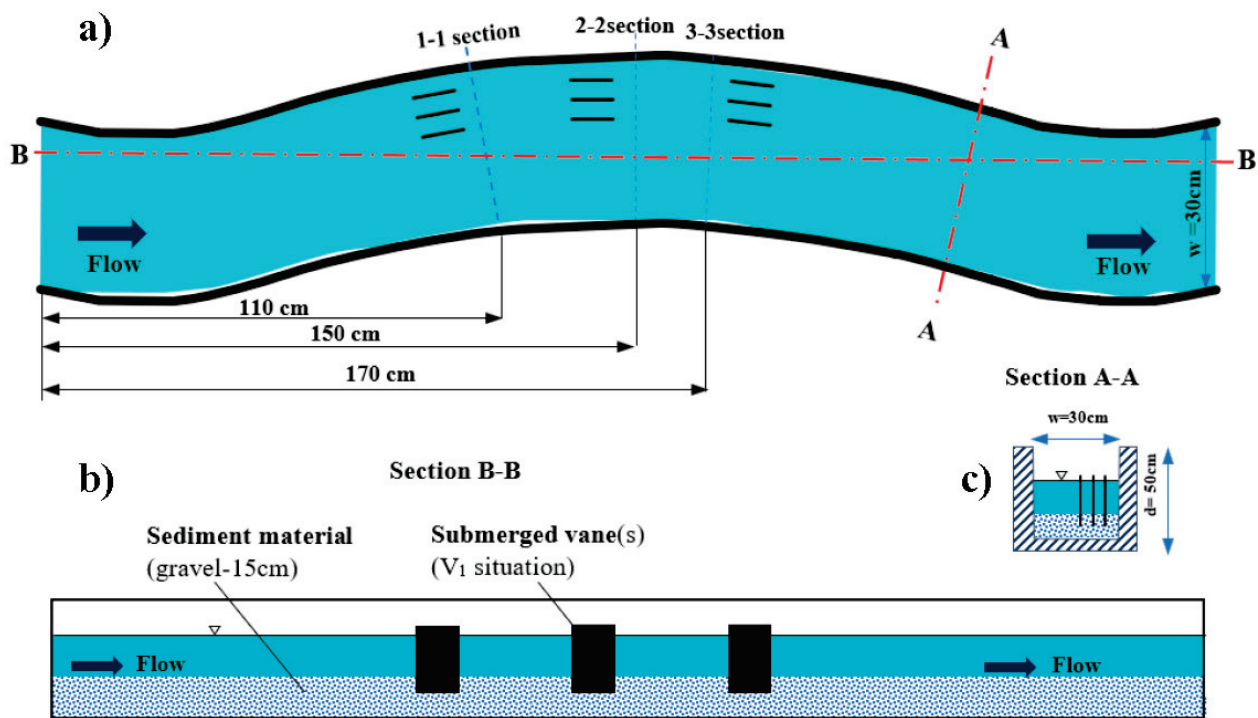


Figure 2. Submerged vane experimental set-up for “with vane” situation: (a) Channel top (plan) view, (b) Cross section view, (c) Section view.

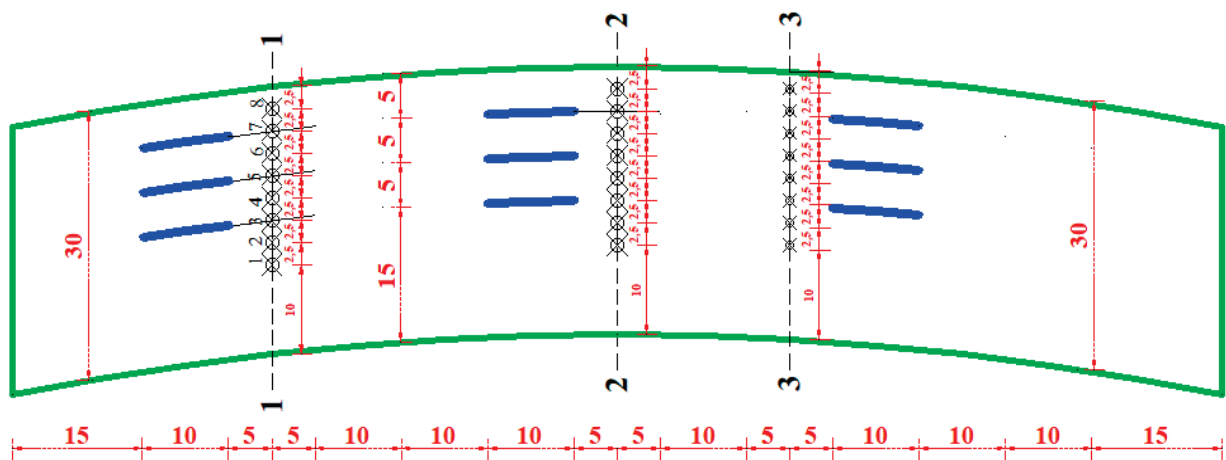


Figure 3. According to “with vane” situation, all sections and points measured in the channel.

Table 2. Presented submerged vane and previously experimental details.

	Presented Study	Odgaard [19]
Vane height/length (cm)	10/10	7.4/15.2
Meander angle (°)	30	90
Bend radius (m)	3.60	11.89
Flow discharge (m ³ /s)	0.025	0.11–0.15
Mean velocity (m/s)	0.900	0.396
Water surface slope	0.0003	0.00064
Mean flow depth (cm)	11 (V ₀ case), 12 (V ₁ case)	17.4 and 18.2

2.2. Mathematical Model

The flow conditions of modeling are turbulent flow and free surface flow which is directed by gravity. According to the literature, this kind of free surface flow can be simulated

by the volume of fluid (VOF) method as water-air 2-phase flow problems. The standard k - ε turbulence model was used in the three-dimensional numerical simulation of flow. The k - ε turbulence model was a possible method for the free surface flow simulations [20,21].

2.2.1. Basic Equations

The investigated open channel flow was a 3D, turbulent, unsteady free surface flow. For the k - ε turbulence model given by [22], the continuity equation, the momentum equation, and the equations for k - ε were given Equations (1)–(6).

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \rho g + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \quad (2)$$

Turbulence kinetic energy (k) equation:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G - \rho \varepsilon \quad (3)$$

Turbulence dissipation rate energy (ε) equation:

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (4)$$

where, t is the time; u_i is the velocity components; x_i is the coordinate components; ρ is the density; g is the gravity; μ is the molecular viscosity; P is the correct pressure; μ_t is the turbulent viscosity, which can be derived from the turbulent kinetic energy k and turbulent dissipation rates:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

$$G = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (6)$$

σ_k and σ_ε are turbulence Prandtl numbers for k and ε equation, respectively, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are ε equation constants, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$. $C_\mu = 0.09$ is a constant, determined by experimentally.

VOF model

In this study, the VOF method was used to calculate the water-air interface. This method was used for 2-phase air-water flow simulation [23] and to compute the free surface of the flow [24]. The VOF method essentially determines whether the element volumes in the computational mesh are empty, partially filled, or completely filled with water. Representing the volumetric filling ratio of the mesh elements, the mesh element is fully filled for $F = 1$, empty (filled with air) for $F = 0$, and partially filled with water for $0 < F < 1$ [25]. In this approach, the tracking interface between air and water is accomplished by the solution of a continuity equation for the volume fraction of water:

$$\frac{\partial \alpha_w}{\partial t} + \frac{\partial \alpha_w u_i}{\partial x_i} = 0 \quad (7)$$

where, α_w is volume fraction of water. In each cell, the sum of the volume fractions of air and water is unity. Volume fractions of air denote α_a can be given as,

$$\alpha_w + \alpha_a = 1; \quad 0 \leq \alpha_w \leq 1 \quad (8)$$

In open channel flows, Ansys-Fluent internally calculates the volume fraction based on the input parameters specified in the boundary conditions. For subcritical inlet flows ($Fr < 1$), Ansys-Fluent reconstructs the volume fraction values on the boundary by using the values from the neighboring cells. For subcritical inlet flows, node values of volume fraction at the boundary must calculate using the cell values and volume fraction at each face of the boundary must calculate using the interpolated node values. For supercritical inlet flows ($Fr > 1$), the volume fraction value on the boundary can be calculated using the fixed height of the free surface from the bottom [26].

2.2.2. Boundary Conditions for Submerged Vanes

Flow field boundary conditions must be specified differently on walls, channel inlet, outlet and free surface, due to unsteady and channel flow. Since the boundary and initial conditions are different for each variable, they must be selected separately. Velocities on free surfaces and at side-bottom channels, velocities on submerged vane faces were obtained using the standard wall function based on the recommendation of Launder and Spalding [22]. This wall function accepts a log-law velocity profile close to the wall and was determined as in Equation (9):

$$\frac{u_p}{u_*} = \frac{1}{K} \ln \left(E \frac{u_* y_p}{\nu} \right) \quad (9)$$

where, " u_p " is the average stream flow velocity at the " p " point; " K " von Karman constant (0.418); " y_p " is the distance from point p to the wall; empirical constant " E " has the value of 9.79; " u_* " is the friction velocity. The " u " uniform velocity distribution was given to the horizontal velocity component in the x -direction at the inflow boundary. The vertical velocity component " v " in the y -direction was set to zero. The inlet velocity field to the channel consists of a forward ' u ' horizontal velocity and zero ' v ' vertical velocities at all points except points close to the channel.

The wall y^+ is a dimensionless distance similar to the local Reynolds number often used in CFD to indicate how the mesh is for a particular flow. It determines whether the effects in cells adjacent to the wall are laminar or turbulent [27].

$$y^+ = \frac{u_\tau y}{\nu} \quad (10)$$

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} \quad (11)$$

where u_τ is the friction velocity, y is the height from the wall to the mid-point of the wall-adjacent cells, ν is the kinematic viscosity, τ_w is the wall shear stress and ρ is the fluid density at the wall. Values of y^+ close to the lower bound ($y^+ \approx 30$) are most desirable for wall functions, whereas values of $y^+ \approx 1$ are better for near-wall modelling [28].

2.2.3. Meshing-Grid Information

In this paper, the 3D analysis was built up for V_0 and V_1 cases. CFD model was created according to the open channel experiment (Figures 1 and 2). Initial and boundary conditions were established according to the experimental study. 1,927,650 meshes for V_0 submerged vane case and for the V_1 case, 1,938,869 meshes were assigned. In addition, tetrahedron-type meshes were used in the design.

The proposed model was used to simulate the variation of submerged vane open channel flow. The biggest problem during the implementation of the submerged vane in the Fluent model was the skewness error of the network grid. The mesh qualities were controlled with equiangular skewness, equisize skewness and aspect ratio in the Gambit program. Skewness and other problems were solved by acquiring a smaller mesh dimension grid line. Since the real shape of the vane was considered in the model, the skewness error was increased due to the shape of the open channel. Those errors were

defined and corrected by increasing the amount of mesh with Gambit. However, when the mesh becomes smaller, the number of mesh was increased. Furthermore, the computational domains for all cases were approximately divided by 1,927,650–1,938,869 tetrahedral mesh volumes to obtain acceptable skewness coefficients. This represents approximately 315,000 nodes. In the meshing cases, the convergence criterion of flow parameters was taken at 0.01 for all runs.

The 3D analysis was built up for V_0 and V_1 cases. The CFD model was created according to the open channel experiment setup consisting of 1 main meander channel (Figures 1 and 2). According to the experimental inlet measure (Table 1), inlet conditions and boundary layer conditions were established. The boundary conditions of the flow formed with V_0 and V_1 cases have been defined. Figure 4 shows the surfaces for the CFD model solution. According to Figure 4, the water inlet height = velocity inlet, submerged vane – open channel surfaces = wall and outlet section (in downstream) = outflow were accepted. In addition, for the flow discharge of 25 L/s, the water inlet height was defined as 9.5 cm.

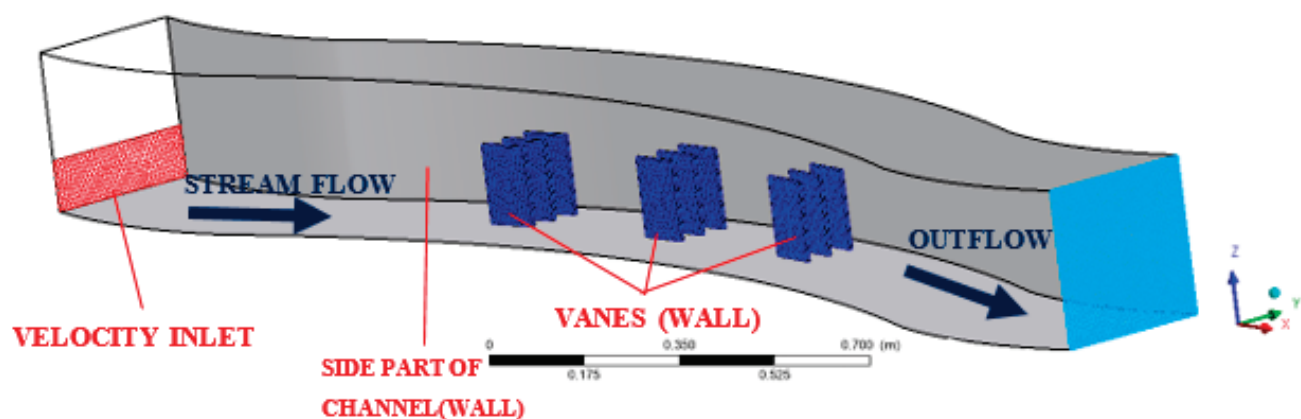


Figure 4. Boundary conditions for “with vanes” situation according to the downstream view.

The mesh independence test was performed by doubling the mesh numbers in the lateral and vertical directions. However, no significant difference in flow velocity results was observed due to mesh improvement. This finding showed that the flow velocity results were independent of the mesh.

2.2.4. Numerical Solver

When the velocity fields in the open channel have complex currents such as circulation flow, turbulent flow and secondary flow problems arise because the open channel flows are nonlinear and velocity–the pressure field interdependent. These problems were solved using the “Coupled” procedure approach. This procedure was the iteration method, and it was based on the prediction-corrector approach. Fluent provides the option to choose “Coupled” pressure-velocity coupling algorithms. The full implicit scheme was used in the model [29]. As an initial state, the inlet channel is first filled with air and water. Next, water at a certain height was released into the free flow at a certain rate from the inlet channel to the upstream end. The channel flow continues until it reaches the downstream limit. The calculation continued for about 600 s, at which point the front had already crossed the downstream boundary and any change in flow area was ignored. A time step of 1 s was chosen after preliminary trials to have the desired converged solution. The discretization methods and solver settings are presented in Table 3.

Table 3. Numerical model details.

Solver Set	Solver Space-Time	Pressure Based 3D, Unsteady
Model	Multiphase Model Viscous Model	VOF $k-\epsilon$
Phase	Primary Phase Secondary Phase	Air water
Discretization	Pressure Momentum	Presto Second order upwind
Pressure-Velocity Coupling	Method	Coupled
Convergence Criterion	Residuals	0.001 (Continuity) 0.001 (Momentum)

3. Results and Discussion

Flow velocity simulations at the measurement points of the Open Channel were investigated experimental and CFD results. In addition, the numerical results of submerged vane structures were examined along the depth for vane and no vane cases flow velocities. In order to see the amount of change after the section, the measured and simulated flow velocity results are dimensionless based on the average velocity (in Table results). Velocity vectoral representation at 0.6 d for without vane and with vane models given in Figure 5a,b.

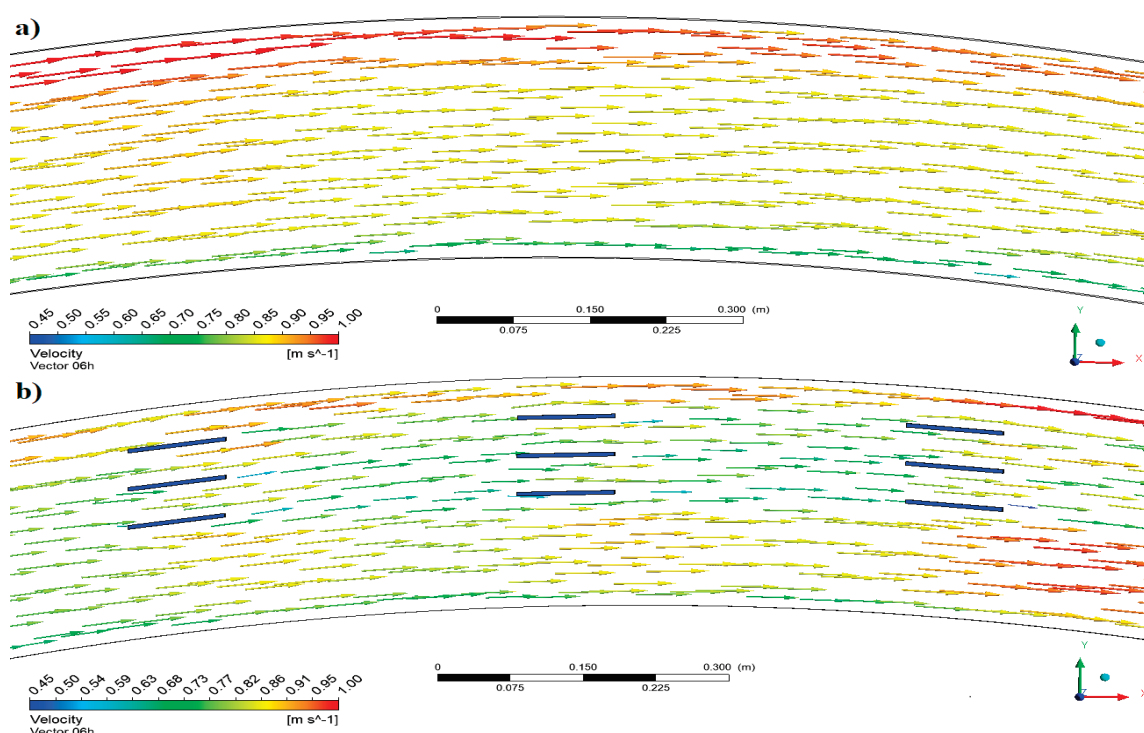


Figure 5. Velocity vectoral representation at 0.6 h for: (a) “without vane” situation, (b) “with vanes” situation.

When Figure 5a,b were examined, it was observed that high flow velocities are observed at the points where the channel bending first starts. The flow velocity increases (from green to “yellow-orange-red”) from the inner bank to the outer bank. When Figure 5b were considered, it was observed that the flow velocity around the vane was reduced (in green color) and between the vanes (yellow color) it had a flow velocity of 0.65–0.75 m/s. It has been seen that flow has a velocity of 0.85–0.93 m/s, near the middle outer bank region and in channel parts without vane (Figure 5a). In order to see the changes in the water

surface, it is given as a velocity contour map in Figure 6 with “without vane” and “with vanes”. As can be seen from the figures, it is observed that the flow is directed around the vane and the flow velocity between the vanes decreases. It is seen that the vane structures are effective in directing the flow and reduce the flow velocity, and the flow reaches balance in the inner bank and outer bank in the section of the channel bend. In Table 4, Figures 7 and 8, CFD results are given with the measured points according to the 1-1, 2-2 and 3-3 sections.

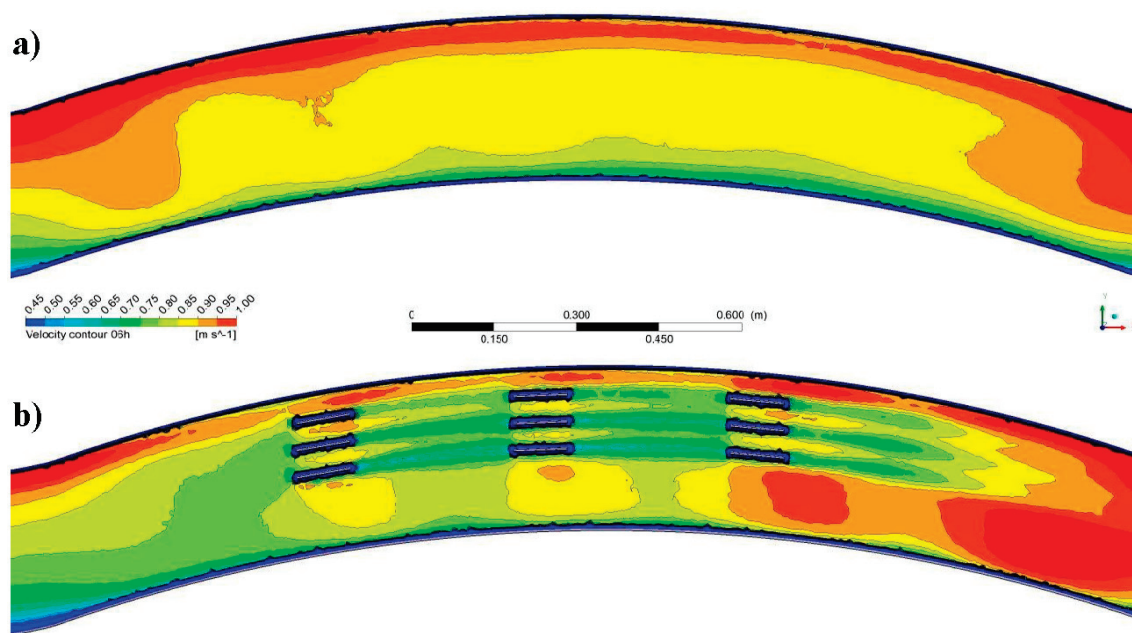


Figure 6. Velocity contour map at the water surface for: (a) without vane situation, (b) with vanes situation.

Table 4. CFD and experimental velocity results for without vane situation at Section 1-1, 2-2, 3-3.

Section No	Point No	Location at x Direction (m)	Location at y Direction (m)	Experiment Results	Fluent CFD Results	Error (%)
1-1	1	1.10	0.247	0.96	0.97	0.97
	2	1.10	0.272	0.98	0.97	1.08
	3	1.10	0.297	0.98	0.97	0.74
	4	1.10	0.322	0.98	0.97	0.67
	5	1.10	0.347	1.02	0.97	4.77
	6	1.10	0.372	1.02	0.99	2.53
	7	1.10	0.397	1.02	1.04	2.78
	8	1.10	0.422	1.04	1.10	5.89
2-2	1	1.50	0.247	0.98	0.97	1.11
	2	1.50	0.272	0.98	0.98	0.21
	3	1.50	0.297	0.97	0.97	0.08
	4	1.50	0.322	0.97	0.97	0.44
	5	1.50	0.347	1.01	0.97	3.68
	6	1.50	0.372	1.01	0.99	2.36
	7	1.50	0.397	1.03	1.05	1.45
	8	1.50	0.422	1.04	1.10	5.17
3-3	1	1.70	0.247	0.96	0.96	0.90
	2	1.70	0.272	0.97	0.97	0.42
	3	1.70	0.297	0.98	0.97	0.67
	4	1.70	0.322	0.99	0.97	1.44
	5	1.70	0.347	1.00	0.99	1.40
	6	1.70	0.372	1.02	1.01	0.72
	7	1.70	0.397	1.04	1.06	2.21
	8	1.70	0.422	1.06	1.07	0.60

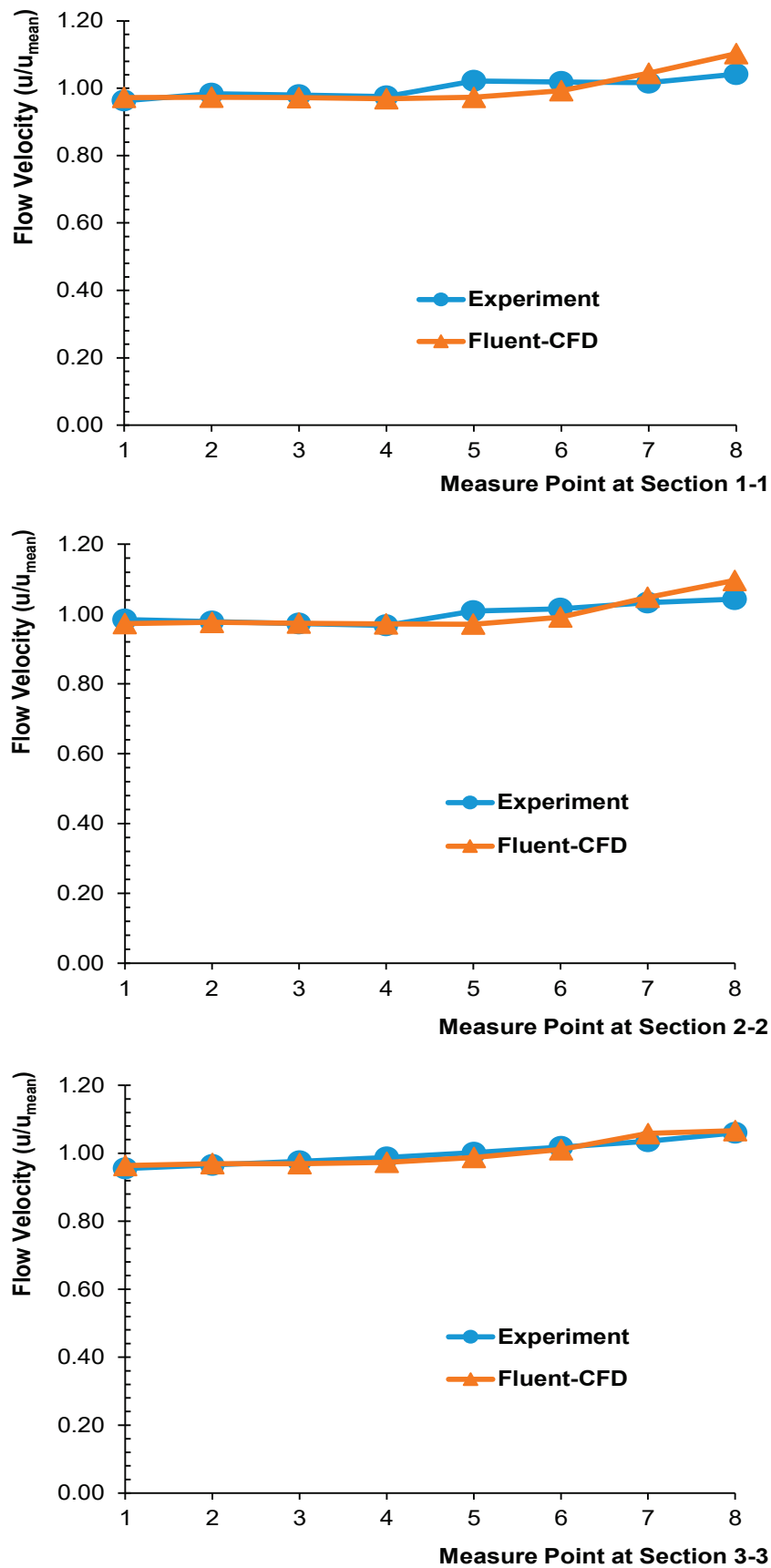


Figure 7. Flow velocity variation for without vane situation at Sections; 1-1, 2-2 and 3-3.

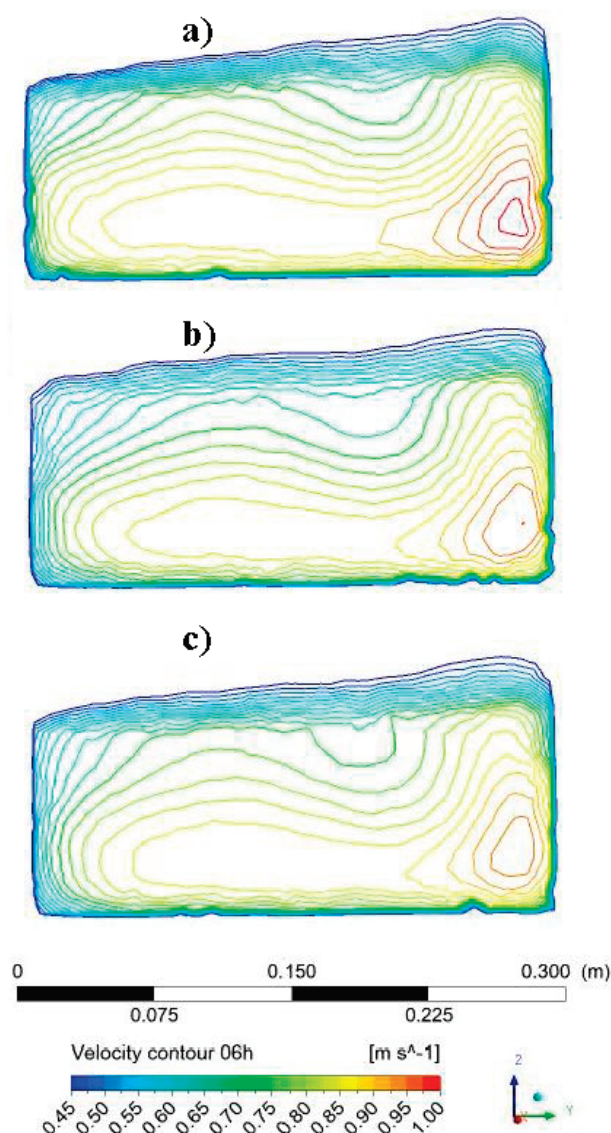


Figure 8. Velocity contours of “without vane” situation for Sections; (a) 1-1 (b) 2-2 (c) 3-3.

In the Figure 7 and Table 4, the flow velocity at sections was accepted as dimensionless velocity “ u/u_{mean} ”. The 1st point represents the point close to the inner bank, and the 8th point represents the point close to the outer bank. The experimental and numerical model velocity values obtained in all sections are shown in Figure 7. Table 4 shows the error rates by comparing the experimental and CFD analysis results. In Figure 8a–c velocity contours of the 1-1, 2-2 and 3-3 cross-sections (without vane situation) are given, respectively.

When the table and graph are examined, it is seen that the error percentage of the velocities is less at the midpoints than at the edges. Maximum error was observed in the outer bank (8th points) for “without vane” situation 1-1 section (5–6%). In general, it has been found that the test and Fluent-CFD results are in good agreement. According to Figure 8a–c, it is seen that the velocity increases in the outer bank and decreases in the inner bank. In addition, as can be seen in the figure, the flow water depth decreases in the inner bank, while the water depth increases in the outer bank (the water depth changes with the blue contour lines). For the without vane situation, it is seen that the experiment and CFD results are generally compatible and the error rates are at a reasonable level.

The experimental and numerical model (“with vane”) velocity values obtained in all sections are shown in Figure 9. Table 5 shows the error rates by comparing the experimental

and CFD analysis results in V_1 case. In Figure 10a–c velocity contours of the 1-1, 2-2 and 3-3 cross-sections (“with vane”) are given, respectively.

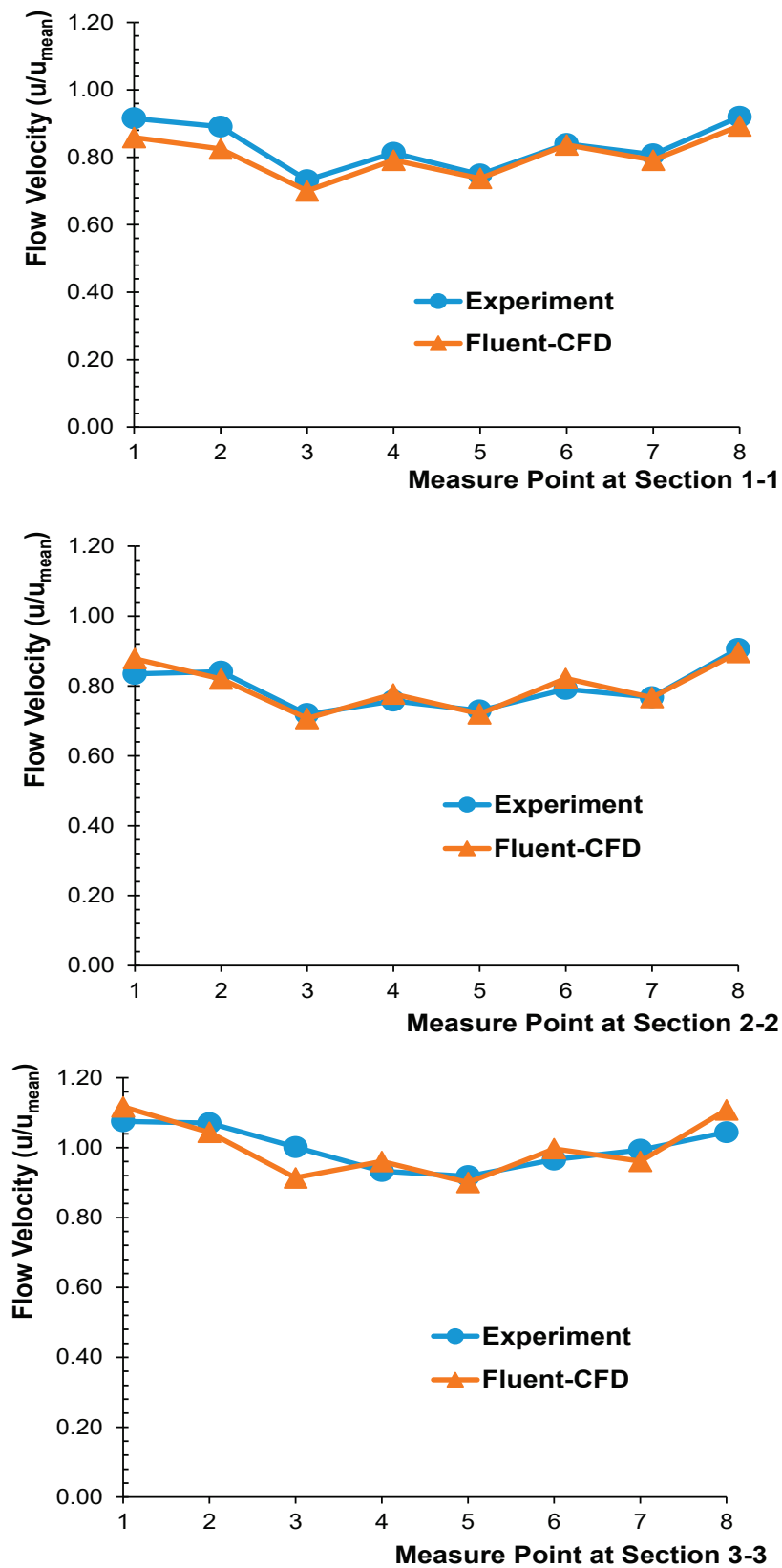


Figure 9. Flow velocity changes for ‘with vanes’ situation at sections; 1-1, 2-2 and 3-3.

Table 5. CFD and experimental velocity results for with vane situation at Sections 1-1, 2-2 and 3-3.

Section No	Point No	Location at x Direction (m)	Location at y Direction (m)	Experiment Results	Fluent CFD Results	Error (%)
1-1	1	1.10	0.247	1.10	1.07	2.81
	2	1.10	0.272	1.07	1.03	4.08
	3	1.10	0.297	0.88	0.87	0.83
	4	1.10	0.322	0.98	0.98	0.91
	5	1.10	0.347	0.90	0.92	2.08
	6	1.10	0.372	1.01	1.04	3.28
	7	1.10	0.397	0.97	0.98	1.46
	8	1.10	0.422	1.10	1.11	0.63
2-2	1	1.50	0.247	1.05	1.10	4.53
	2	1.50	0.272	1.06	1.03	3.10
	3	1.50	0.297	0.91	0.89	2.31
	4	1.50	0.322	0.95	0.97	1.96
	5	1.50	0.347	0.92	0.90	1.93
	6	1.50	0.372	1.00	1.03	3.17
	7	1.50	0.397	0.97	0.96	0.71
	8	1.50	0.422	1.14	1.12	1.70
3-3	1	1.70	0.247	1.08	1.10	2.35
	2	1.70	0.272	1.03	1.03	0.32
	3	1.70	0.297	0.99	0.93	6.32
	4	1.70	0.322	0.94	0.93	0.75
	5	1.70	0.347	0.93	0.93	0.37
	6	1.70	0.372	0.95	0.98	2.77
	7	1.70	0.397	1.03	1.00	3.48
	8	1.70	0.422	1.05	1.11	5.79

When the Table 5 was examined, maximum error was observed in 3-3 section (6.32%) for “with vane” situation. In general, it has been found that the test and Fluent-CFD results are in good agreement.

When the table and figures were examined, maximum error was observed in 3rd point) for “with vane” situation 3-3 section (6.32%). In general, it has been found that the experiment and Fluent-CFD results are in good agreement.

According to Figures 8 and 10, decreases in flow velocities are seen behind the vane. For the 1-1 section without the vane (Figures 8a and 10a), it was observed that the flow velocity decreased from 0,89 m/s to 0,70 m/s (3. point). It has been determined that there is a nearly 21% decrease in flow velocity. Compared to the 2-2 section without the vane (Figures 8b and 10b), it was observed that the flow velocity decreased from 0,93 m/s to 0.77 m/s (7. point). It has been determined that there is a nearly 18% decrease in flow velocity. Finally, the 3-3 section without the vane (Figures 8c and 10c), it was observed that the flow velocity decreased from 0,99 m/s to 0,72 m/s (5. point). It has been determined that there is a nearly 27% decrease in flow velocity. In addition to investigations of flow velocities, water levels for the V_0 and V_1 cases were also investigated. Water level changes given numerical contour with Vof in Figure 11 for V_0 and V_1 cases. In addition, CFD -water depth changes (as cm) in V_0 and V_1 case at for all sections.

When the depth changes in sections 1-1, 2-2 and 3-3 are examined (Figures 11 and 12), it is observed that generally submerged vanes increase the water depth. The most obvious change in section 1-1 (Figure 12a) was the increase in water height from 11 cm to 11.66 cm at the 5th point. It has been observed that it increases the water depth by about 6%. In section 2-2, it was observed that while the depth of flow increased slightly in the middle of the channel, the depth decreased at points 1 and 7 close to the outer and inner slope (Figure 12b). In the 3-3 section, it showed a similar change to the 1-1 section and the water level increased from 11 cm to 11.87 cm (Figure 12c). In the 3-3 section, the water depth increased by about 8% in the V_1 case compared to the V_0 case. When the changes in % are examined (Figure 12d), it can be said that there is a greater increase in the 1-1 and 3-3 sections than in the 2-2 sections.

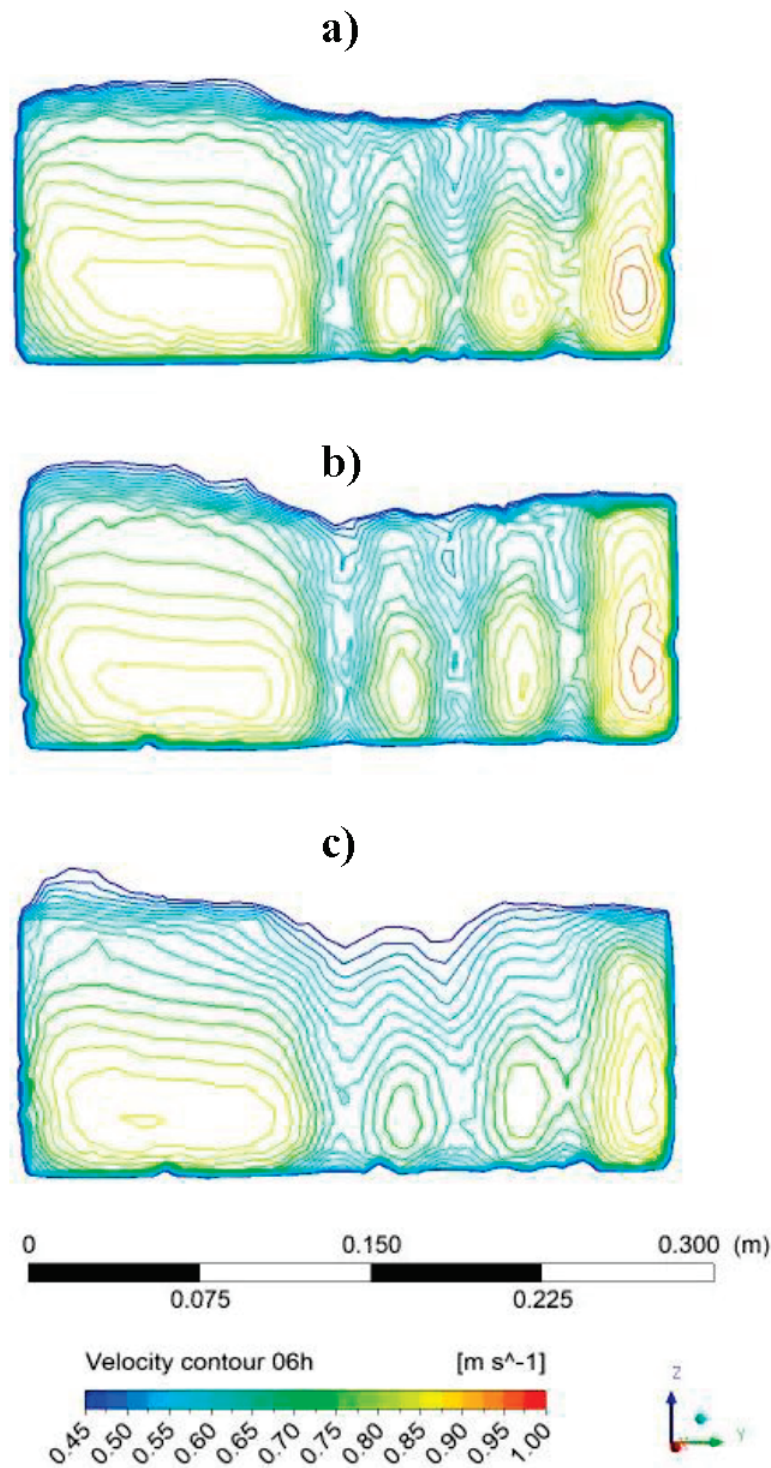


Figure 10. Velocity contours of ‘with vanes’ situation analysis (a) Section 1-1, (b) Section 2-2, (c) Section 3-3.

When all the velocity changes behind the submerged vane are examined (Figure 13), it is seen that the maximum velocity change (27%) is at the 3-3 section and at the 7. point, while the minimum change (16%) is at the 2-2 section and at the 5. point. For the velocity change between the vane, it is seen that the “maximum” velocity change (26%) is at the 3-3 section and at the 4. point, while the minimum change is at the 2-2 section and at the 6. Point (Figure 13).

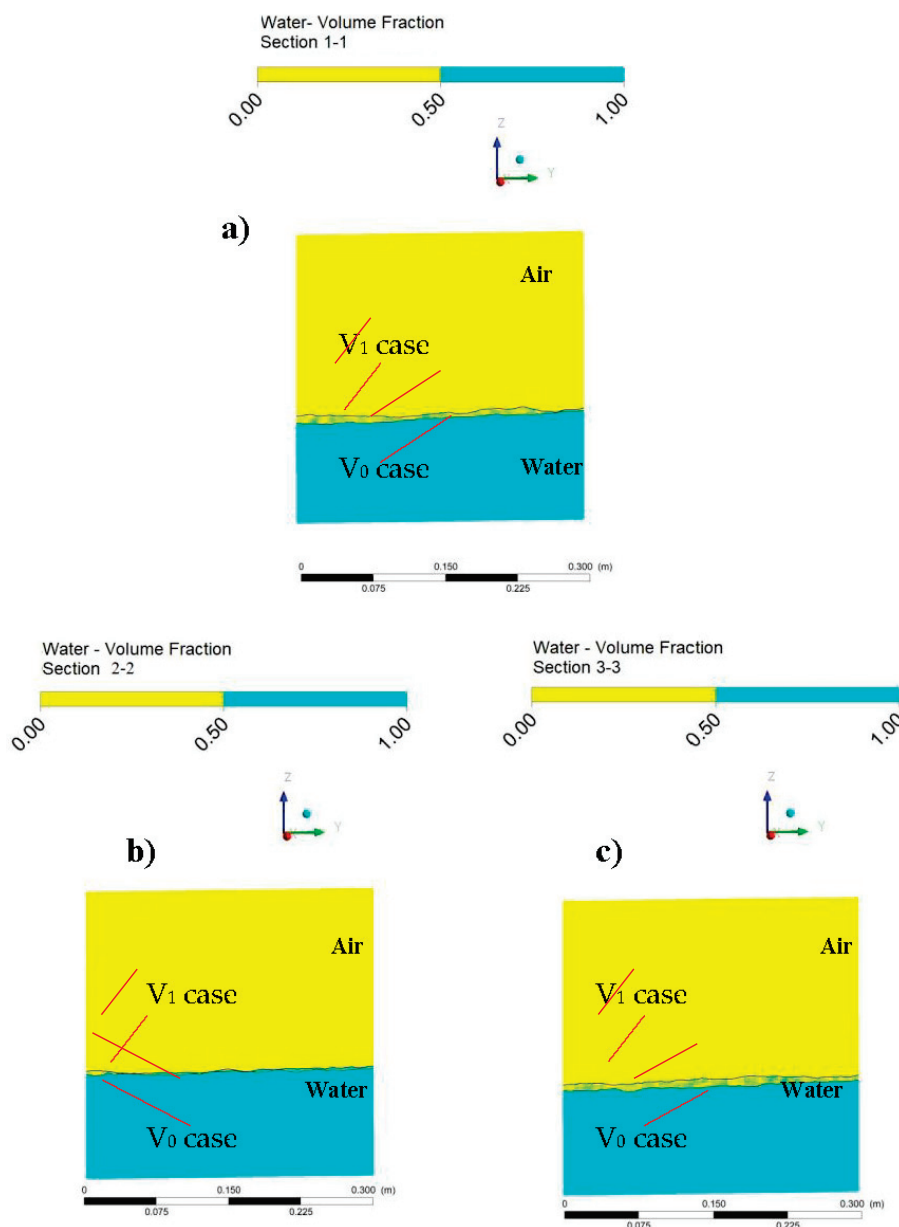


Figure 11. CFD -water level changes (m) in V_0 and V_1 case at (a) 1-1, (b) 2-2, (c) 3-3 sections.

In Figures 14 and 15, it was observed that while the mean velocities were approximately 0.75–0.83 m/s in the vaneless outer meander, these velocities decreased to an average of 0.61–0.68 m/s in the vaneless outer meander along the water depth. According to the after-vane structure's measurements, the submerged vanes reduced flow velocity by 21% in section 1-1, and decreased the flow velocity by 19% and 20% in sections 2-2 and 3-3, respectively.

Flow velocity profiles made without a submerged vane are compatible with numerical model or experiment results [19,30]. Reported laboratory experiments show flow patterns of submerged vanes. Scour in the outer meander was caused by the increase in flow velocity and shear stress. The submerged vane cuts off secondary circulation or cross flow cuts off thereby reducing high velocities around the outer meander (Figures 10, 11 and 15). This study investigated the effects of submerged vane structures on flow rates and water depth. As a result of this study, it was determined that submerged vane structures decrease the maximum and average velocity along the depth, decrease the flow velocity at 06 d and direct it to the inner bank. In the meander section of the open channel, velocity distribution diagrams of the submerged vaneless streamflow bed (Figures 7 and 8) show that it slides

out of the meander and reaches the maximum level near the outer meander before the outlet of the meander. This experimental pattern was consistent with experimental measurements in the other channel meander [19]. The centrifugal force increases proportionally with the square of the flow velocity and the upper region with high flow velocity reaches more centrifugal force than the lower region [30]. Experimental flow velocity results measured at 0.6 d, modeled both with submerged vane and without submerged vane, showed that the model with submerged vane decreased the flow velocity by 16–27% and directed the flow (Figures 7, 9 and 11). When the literature studies were examined, Gemici [7] experimentally found that submerged vane flow velocities were reduced by 7–19%. The flow models obtained with the 3D model were examined along with the depth (Figure 11), and it was observed that the mean velocity was reduced by 19–21% (Figures 14 and 15). The result of this study will be useful for understanding the flow phenomenon, validation of numerical work and subsequent design of meander protection measures.

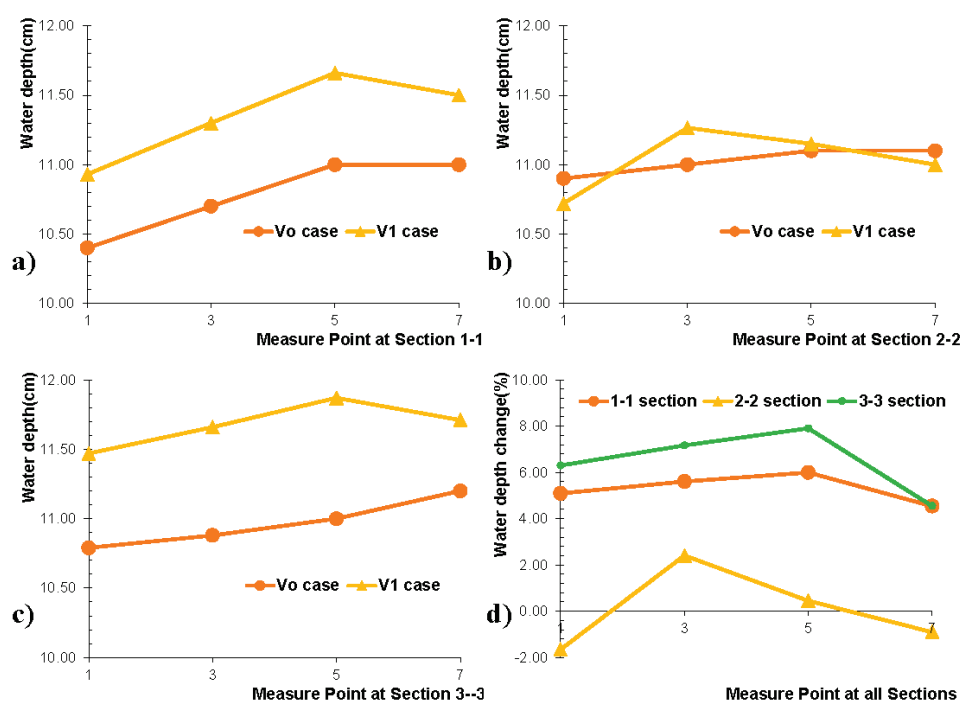


Figure 12. CFD-water depth changes (cm) in V_0 and V_1 case at (a) 1-1, (b) 2-2, (c) 3-3 sections and (d) % change for all sections.

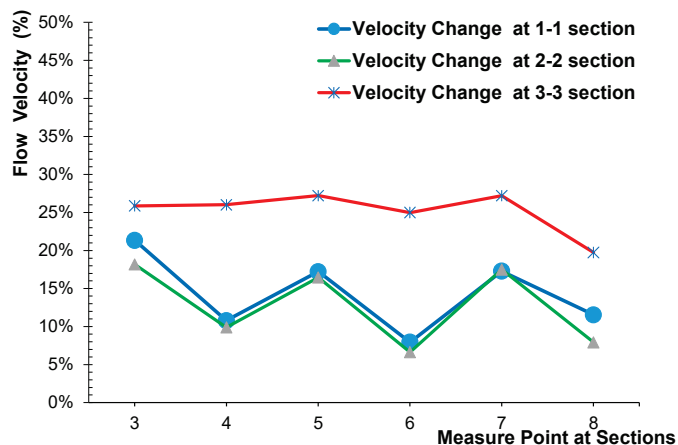


Figure 13. Flow velocity change according to 1-1, 2-2 and 3-3 sections for behind the submerged vane.

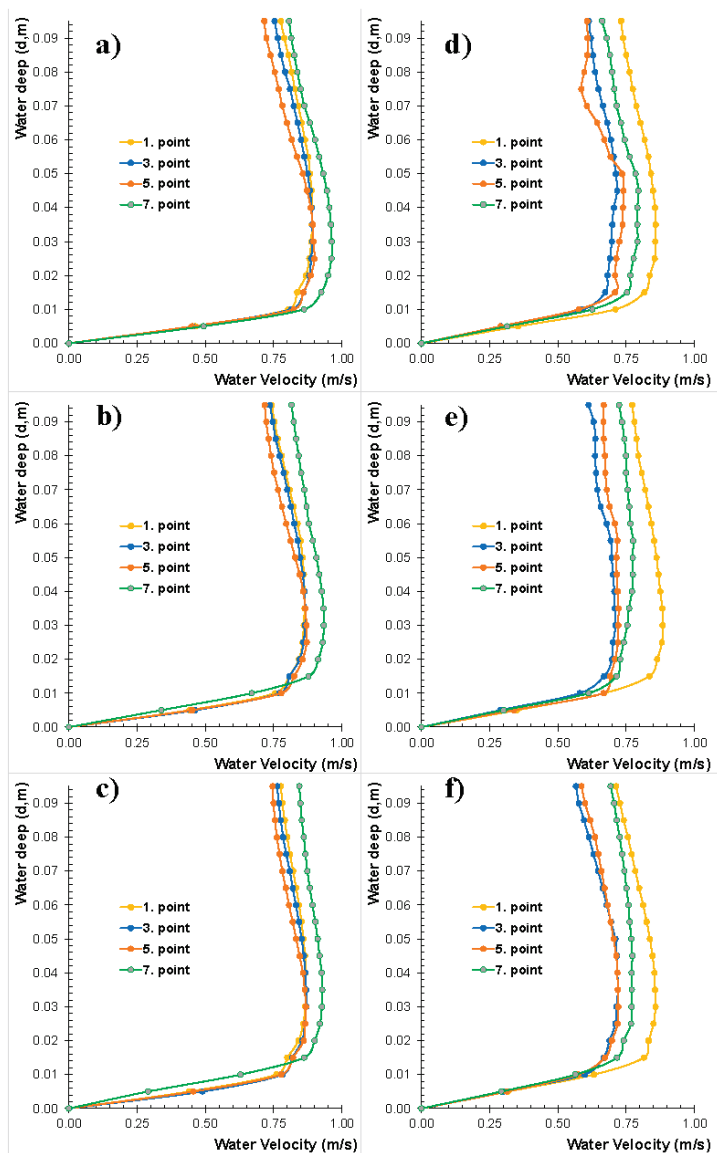


Figure 14. CFD -Velocity changes (m/s) along the water depth (m) in V_0 case points at (a) 1-1, (b) 2-2, (c) 3-3 sections and V_1 case points at (d) 1-1, (e) 2-2, (f) 3-3 sections.

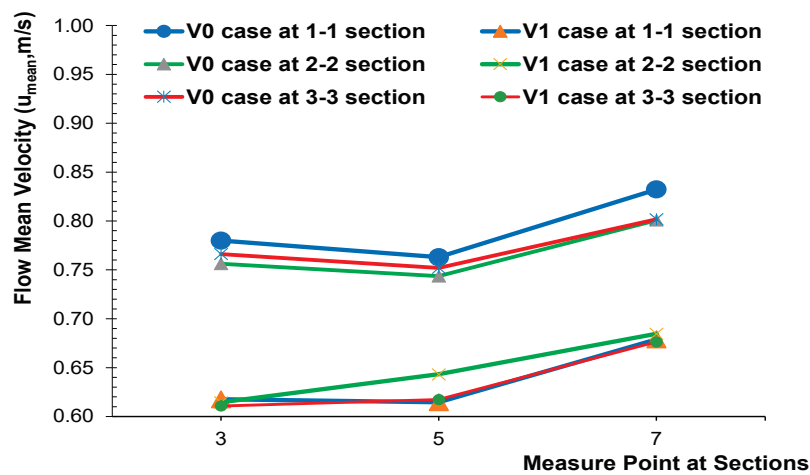


Figure 15. Flow velocity change according to the V_0 case and V_1 case.

4. Conclusions

In this study, the performance of without vane and 3-array vane models in open channel flows has been investigated by using a flow velocity of 25 L s^{-1} . The numerical results of the flow velocities were confirmed by experimental results. The effect of the vane structure on the flow velocity measured in the flow channel was determined and the 3 sectional velocity changes of the 3-array with 3 submerged vane (“with vane”) structures were compared experimentally and numerically to each other. The following results can be derived from this study:

- The simulated CFD velocity for the without vane and 9 (3×3) vane cases were compared with the measured data. If the results of the experiments are examined in accordance with the CFD simulation results, a lower error has been detected. Figure 1. Flow velocity changes for ‘with vanes’ situation at sections; 1-1, 2-2 and 3-3. When the experimental and CFD results were examined, the maximum error was observed as 6.32%.
- It was found that 3 vane structures in 3-array affect the mean flow velocity by 27% and minimum flow velocity by 16% at 0.6 d.
- The flow velocities were investigated along with depth using the CFD and found that the mean velocity was reduced by 14–21% along the depth.
- Submerged vane structures balance the flow of water depth on the inner bank with the water depth on the outer bank within open channel flows. It reduced the flow velocity by directing the water depth and flow velocity from the outer bank to the inner bank.
- When the depth changes in sections are examined, it is observed that generally submerged vanes increase the water depth. In the sections, the water depth increased by about 6–8% in the V_1 case compared to the V_0 case.

Vane structures were found to be effective in regulating flow. It is also recommended that submerged vane structures be applied effectively in reducing flow velocities and directing stream flows.

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Article

Floating Photovoltaic Plants as an Effective Option to Reduce Water Evaporation in Water-Stressed Regions and Produce Electricity: A Case Study of Lake Nasser, Egypt

Mohamed Abdelgaied ¹, Abd Elnaby Kabeel ^{1,2}, Martina Zelenáková ^{3,*} and Hany F. Abd-Elhamid ^{4,5}

¹ Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta 31521, Egypt

² Faculty of Engineering, Delta University for Science and Technology, Gamasa 35712, Egypt

³ Institute of Circular and Sustainable Construction, Faculty of Civil Engineering, Technical University of Košice, 040 01 Košice, Slovakia

⁴ Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt

⁵ Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Košice, 040 01 Košice, Slovakia

* Correspondence: martina.zelenakova@tuke.sk

Abstract: Water resources are considered one of the most critical and indispensable elements to ensure the survival of all living organisms on the planet. Since there is a close relationship between water, energy, and food security, this interdependence presents a major global societal challenge. While Egypt is one of the countries that suffers the most from water poverty, it has Lake Nasser which is considered one of the largest artificial lakes in the world, with an estimated area of about 5250 km². Hence, this work aims to conserve such water resources while addressing two critical issues related to water and energy. To achieve this goal, this study proposed the use of partial coverage technology on Lake Nasser with floating photovoltaic (FPV) panels. The results of the study showed that the partial coverage of Lake Nasser with FPV panels represents a very effective proposal to preserve the water resources of Egypt, which suffers from water poverty. The savings in water evaporation in Lake Nasser reached 61.71% (9,074,081,000 m³/year) and the annual rate of electricity production was 467.99 TWh/year when 50% of the area of Lake Nasser was covered with FPV panels.

Keywords: water scarcity; floating photovoltaic; water evaporation reduction; electricity generation; Lake Nasser; Egypt

1. Introduction

In the twenty-first century, water scarcity has become one of the main problems facing all countries in the world, as nearly two-thirds of the world's population suffers from water stress for at least a month each year, in addition to about half a billion people who suffer daily from severe water shortages [1,2]. Water is not only used for humans, but is also used in agriculture and food production. In many regions around the world, the extraction of water resources and their delivery to consumers or agricultural land depends largely on energy. Hence, there is a close interdependence between water resources, food, and energy, for which reason the Food and Agriculture Organization of the United Nations (FAO) was established [3,4]. Ensuring the continuity of food supplies for the global population requires the preservation of water resources as well as the availability of energy, and this represents a significant challenge for the global community [5,6]. A recent study indicated that agricultural land irrigation is the world's largest consumer of fresh water, as it consumes about 70% of water resources. This percentage rises to 90% in developing countries compared to 60% in developed countries [7]. Hence, for developing countries that suffer from water poverty, any approach that can conserve water resources, especially in areas with hot and dry weather, will be a fundamental solution not only from the point

of view of food security, but also an effective case in terms of economic development. Globally, basins are used for drinking and irrigating crops. As there are approximately 277,400,000 small-scale irrigation basins (<10,000 square meters) and 24,120,000 large-scale irrigation basins (10,000–100,000 square meters), these basins represent more than 90% of the standing water used in irrigation of crops globally [8,9].

The surface evaporation of water in ponds, lakes, and reservoirs is an important factor in water loss due to its exposure to direct sunlight. Therefore, surface evaporation of water represents one of the factors of the water scarcity problem in many countries of the world, especially remote areas. Creating a shadow on the surface of the water is one of the ways to reduce the rates of surface evaporation of water in ponds, lakes, and reservoirs [10]. This shade can be achieved by placing floating photovoltaic cells on the surface of the water [11]. The floating photovoltaic cells on the surface of the water are characterized by reducing surface evaporation rates and improving the efficiency of photovoltaic cells [12]. The installation of photovoltaic panels on water bodies is an effective alternative to traditional methods where photovoltaic panels are installed on the ground [13]. Japan was the first country to build floating photovoltaic systems on water bodies and to compare its performance with that of conventional photovoltaic systems for research purposes [14]. Floating photovoltaic panels are installed on natural water bodies such as lakes, reservoirs, dams, and ponds [15]. The technology of floating photovoltaic panels on natural water bodies has attracted worldwide attention since 2007, when a limited number of medium and large-capacity floating photovoltaic power stations were established in many American and Asian countries [16]. The floating photovoltaic panels effectively shade the water surface and thus, help reduce surface evaporation rates and reduce water loss [17]. Photovoltaic panels can be installed on the surface of the water in different ways. It should be noted that the main motive behind the use of floating photovoltaic (PV) systems is to avoid the purchase or lease of land and, most importantly, to improve the efficiency of PV panels.

Floating photovoltaic panels on water bodies are characterized by a higher level of electrical efficiency due to their cooling by water vapor [18,19]. Since floating photovoltaic panels are characterized by their ability to reduce surface evaporation rates from water bodies as well as generate electricity, floating photovoltaic systems can contribute to the stability of the agricultural and electricity generating sectors [20,21]. Many researchers have studied the effect of photovoltaic systems on the relationship between water, food, and energy [22–24]. Padilha et al. [25] studied the possibility of using photovoltaic plants in arid regions of Brazil to increase water security and power generation. They mentioned that the surface evaporation of water in dam reservoirs represents one of the main obstacles to achieving water stability in the arid regions of Brazil, and they found that the use of floating photovoltaic systems reduced the rates of surface evaporation and electricity generation in these areas [26]. They also conducted an economic feasibility study for the use of such projects [27,28].

By reviewing the previous studies, it was found that the use of floating photovoltaic panels to reduce water evaporation rates in water bodies, whether lakes, ponds, or water reservoirs, has a positive effect in terms of reducing water losses and electricity production. Hence, the use of floating photovoltaic panels conserves water resources while addressing the two important issues of water and energy, thus achieving the United Nations Sustainable Development Goals. Egypt is one of the first countries to suffer from water poverty and thus, contains Lake Nasser, one of the largest artificial lakes in the world with an estimated area of about 5250 km². This work aims to conserve such water resources while addressing the two important issues of water and energy, thus striving for achievement of the United Nations Sustainable Development Goals. To achieve this, the study proposed the use of partial coverage technology for Lake Nasser with floating photovoltaic panels to reduce the rates of surface evaporation of water and generate electricity, while at the same time preserving fish wealth. This study dealt with four proposals to cover Lake Nasser with floating photovoltaic (FPV) panels at different coverage rates: 50%, 40%, 30%, and 20%.

2. Data and Methods

The freshwater limitation represents one of the most important and most dangerous problems facing the Arab Republic of Egypt, and since Egypt lies below the water poverty line, this research aimed to reduce water evaporation rates from water bodies. This research examined the effect of floating photovoltaic panels on surface water evaporation rates in Lake Nasser, Aswan, Egypt. Given the results of this study, they fall into the category of applied research.

First, the location of Lake Nasser was determined and data about the lake collected. Second, the surface water evaporation rates were calculated for open water surface with and without FPV panels. Third, the volume of evaporation water savings was calculated. Lastly, the amount of electrical power that could be produced from the FPV panels was determined. All the above data was calculated using climate and radiation data for the location of Lake Nasser.

2.1. Reservoir Area Determination of Lake Nasser

Lake Nasser, or the High Dam Lake, is one of the largest artificial lakes in the world, located in southern Egypt, south of Aswan (22°25' N 31°45' E), and in northern Sudan. The name Lake Nasser is given to the largest part that lies within the borders of Egypt and represents 83% of the total area of the lake, while the remaining part located within the borders of Sudan is called Lake Nuba. It was formed as a result of the water accumulated behind the High Dam after its construction (which lasted from 1958 to 1970), with a length of 500 km, an area of about 5250 km², and a depth of 180 m with a total storage capacity of 162 billion cubic meters, making it the largest artificial lake in the world and the second largest lake by area (Figures 1 and 2).



Figure 1. Location of Lake Nasser, Egypt.



Figure 2. Image of Lake Nasser, south of Aswan, Egypt (22°25' N 31°45' E).

2.2. Estimation Method of Surface Water Evaporation Rates

This section presents the method used to estimate surface water evaporation rates with and without floating photovoltaic panels.

2.2.1. Evaporation Estimation for Open Water Surface without Floating Photovoltaic Panels

Water evaporation from the open water surface of Lake Nasser without a floating photovoltaic structure was estimated by using the Penman-Monteith equation [6,29]:

$$E' = \frac{0.408 \Delta (Q - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34) u_2} \quad (1)$$

where E' is the average evaporation per day (mm/day); G is the heat flux in soil, which is zero for water; Q is the daily average irradiation balance (MJ/m²/day); Δ is the slope of saturation vapor pressure curve; γ is the psychrometric constant (kPa/°C); u_2 is the wind speed on a height of 2 m (m/s); T_a is the average ambient air temperature (°C); e_s is the saturated vapor pressure (kPa); e_a is the actual vapor pressure (kPa). The values of γ , Δ , e_s , and e_a are calculated as follows [29–31]:

$$\gamma = 0.665 \times 10^{-3} \times P_{atm} \quad (2)$$

$$\Delta = \frac{4098 e_s}{(T_a + 273)^2} \quad (3)$$

$$e_s = 0.6108 e^{\left(\frac{17.27 T_a}{T_a + 273}\right)} \quad (4)$$

$$e_a = \frac{e_s RH}{100} \quad (5)$$

2.2.2. Evaporation Estimation for Incorporating Floating Photovoltaic Panels

Water evaporation from Lake Nasser covered by the floating photovoltaic structure depended on the PV panel configurations.

The total irradiation from Lake Nasser covered by the floating photovoltaic panels (Q_{tot}) consisted of the surface area covered by floating photovoltaic panels and the irradiation underneath the area covered by the floating photovoltaic panels (Q_{under}), calculated as [29–31]:

$$Q_{tot} = Q (1 - x) + (x Q_{under}) \quad (6)$$

The irradiation underneath the area covered by floating photovoltaic panels (Q_{under}) depended on the long-wave and shortwave radiation, calculated as:

$$Q_{under} = 0.1 \sigma T_w^4 (0.56 - 0.0092 \sqrt{e_a}) \quad (7)$$

Finally, the water evaporation from Lake Nasser covered by the FPV structure (E'_{FPV}) was calculated as follows [29–31]:

$$E'_{FPV} = (1 - x) E'_{tot} \quad (8)$$

$$E'_{tot} = \frac{0.408 \Delta (Q_{tot} - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34) u_2} \quad (9)$$

where x is the ratio between the water surface covered by the FPV structure to the total Lake Nasser flooded area; T_w is the water temperature (K); and σ is the Stefan-Boltzmann constant (4.903×10^{-9} MJ/m² K⁴ day).

2.2.3. Volume of Evaporation Water Savings

The volume of evaporation water savings, EWS (m³/year), was calculated as follows [29]:

$$EWS = (E' - E'_{FPV}) A_{res} \times 10^3 \times 365 \quad (10)$$

where A_{res} is total Lake Nasser flooded area (km²).

2.3. Design of the Floating Photovoltaic (FPV) System

The objectives for covering Lake Nasser with an FPV system were to reduce evaporation from the water surface by placing the units on a floating platform with polyethylene, and to increase the efficiency of electricity generation by directing them towards the south at an angle of inclination equal to the latitude angle of the city of Aswan (Figure 3).

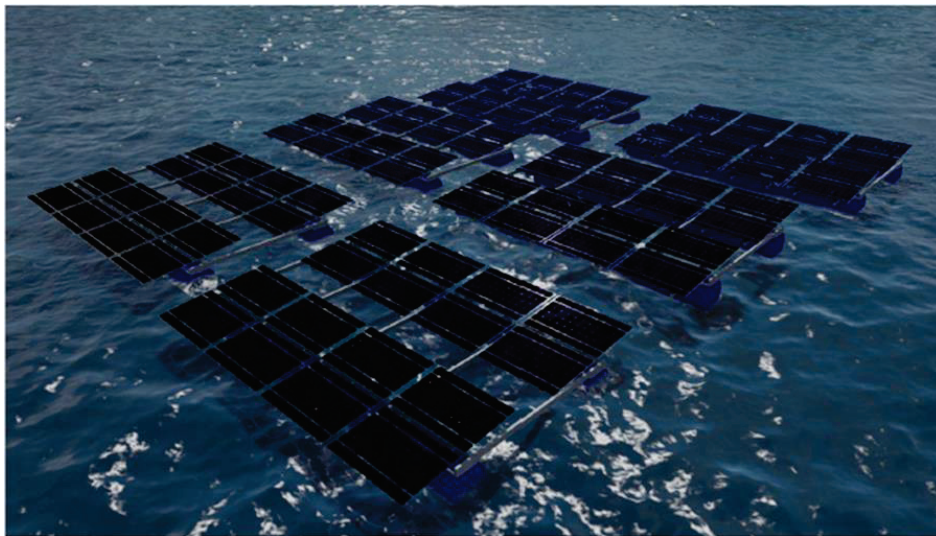


Figure 3. Photo of floating photovoltaic (FPV) panels.

The floating platform consisted of several photovoltaic panels of the type (AE HM400M6-72) 400 W monocrystalline modules. The number of FPV panels utilized in this study depended on the area proposed to be covered. These FPV panels were connected in series and placed in multiple rows, with each series connected to the MPPT input of the inverter. These inverters were connected to a transformer fixed on the ground and connected to a high-voltage transmission network. The platform area of each FPV panel utilized in this study was 1.979 m × 1.002 m and 1.983 m².

Solar radiation and cell temperature are the two most important factors affecting the output power of a photovoltaic unit. Therefore, it was necessary to calculate the cell temperature first in order to calculate the output power of the PV modules. To calculate

the output power of the PV modules, it was necessary to know the optical and thermal properties of all materials used in the manufacture of PV modules, and this data was obtained from the PV module manufacturer. The cell temperature (T_m) and module output power (P_m) were calculated as follows [29,32]:

$$T_m = T_a + \left(\frac{G_T}{G_{T,NOCT}} \right) \left(\frac{9.5}{5.7 + 3.8 u} \right) (T_{NOCT} - T_{a,NOCT}) \left[1 - \frac{\eta_m}{\tau \alpha} \right] \quad (11)$$

$$P_m = P_{Peak} \left(\frac{G_T}{G_{St}} \right) [1 - \alpha_T (T_m - T_{St})] \quad (12)$$

where T_a is the temperature of ambient air ($^{\circ}\text{C}$); G_T is the intensity of total irradiance on module surface (W/m^2); $G_{T,NOCT} = 800 \text{ W}/\text{m}^2$; u is the wind speed (m/s); T_{NOCT} is the nominal operating cell temperature $T_{NOCT} = 45 \text{ }^{\circ}\text{C}$; $T_{a,NOCT} = 20 \text{ }^{\circ}\text{C}$; η_m is the module efficiency and is given by 21.2%; $\tau \alpha$ is the coefficient of transmittance absorptance which can be estimated as 0.9; P_{Peak} is the peak power of module (400 W given by manufacturer); $G_{St} = 1000 \text{ W}/\text{m}^2$; $\alpha_T = -0.38\% \text{ }^{\circ}\text{C}$; and $T_{St} = 25 \text{ }^{\circ}\text{C}$.

After calculating the output power for each module, it was multiplied by the total number of the modules, which depended on the percentage of water surface coverage with FPV panels, to calculate the power produced from all modules. The overall system efficiency (η_{sys}) was calculated by giving the cable efficiency ($\eta_{cable} = 99.4\%$), inverter efficiency ($\eta_{inv} = 97.5\%$), and transformer efficiency ($\eta_T = 97\%$). The AC power at the output of the transformer and at entering the transmission line was calculated as:

$$\eta_{sys} = \eta_{cable} \eta_{inv} \eta_T \quad (13)$$

The output AC power supplied to transmission line was calculated as:

$$P_{output, AC} = P_m \eta_{sys} \quad (14)$$

3. Results

To explore the best way to use the FPV panels technique, four different cases were studied:

- Case study 1: 50% of the total submerged area was covered by FPV panels.
- Case study 2: 40% of the total submerged area was covered by FPV panels.
- Case study 3: 30% of the total submerged area was covered by FPV panels.
- Case study 4: 20% of the total submerged area was covered by FPV panels.

Figure 4 shows the data of average daily solar irradiation and average daily ambient temperature that were imported from the Egyptian Surface Meteorology and Solar Energy Database of the city of Aswan, Egypt ($22^{\circ}25' \text{ N } 31^{\circ}45' \text{ E}$).

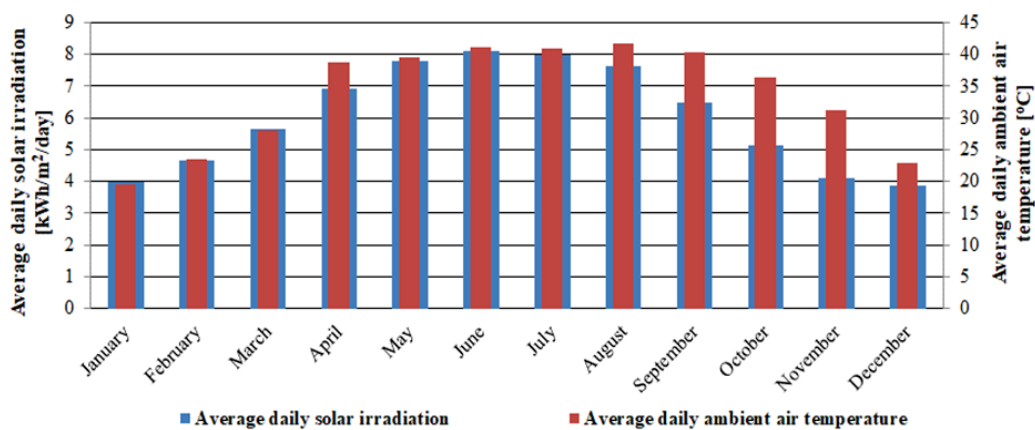


Figure 4. Average daily solar irradiation and daily ambient temperature of the city of Aswan, Egypt ($22^{\circ}25' \text{ N } 31^{\circ}45' \text{ E}$).

3.1. Evaporation Savings

This section presents the effect of partial coverage of Lake Nasser with FPV panels on water surface evaporation rates. This study dealt with four proposals for partial coverage of Lake Nasser with FPV panels to show the effect of these four proposals on the results of evaporation water savings.

The collected parameter values, as well as the estimated values of the variables that do not depend on the FPV panels proposed in this study, are summarized in Table 1. In addition, the values of the collected parameters and the calculated values of the variables for the four cases proposed with different coverage rates of 50% (Case study 1), 40% (Case study 2), 30% (Case study 3), and 20% (Case study 4), are summarized in Tables 2 and 3.

Table 1. Parameters and variables calculated for Lake Nasser, city of Aswan, Egypt (22° 25' N 31° 45' E).

Months	A_{res} (km ²)	Q (MJ/m ² /Day)	T_a (°C)	E' (mm/Day)
January	5250	14.309	19.5	3.933
February	5250	16.779	23.5	4.853
March	5250	20.347	28	6.146
April	5250	24.934	38.6	9.026
May	5250	27.992	39.5	9.844
June	5250	29.207	41.1	10.447
July	5250	28.697	40.9	10.294
August	5250	27.521	41.7	10.215
September	5250	23.287	40.2	9.002
October	5250	18.465	36.3	7.303
November	5250	14.819	31.2	5.780
December	5250	13.917	22.8	4.356

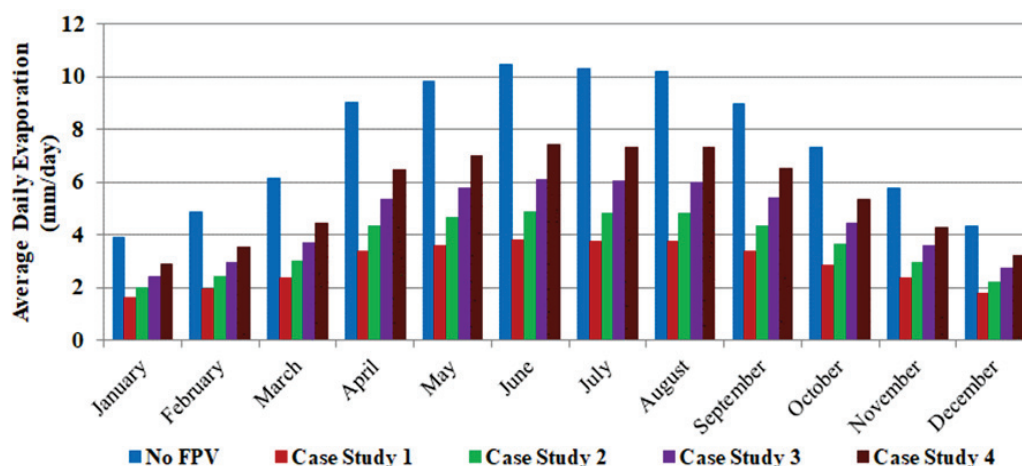
Table 2. Water evaporation savings results (Case Study 1 and Case Study 2).

Months	Case Study 1					Case Study 2					
	x	Q_{tot} (MJ/m ² /Day)	E'_{FPV} (mm/Day)	$EWS \times 10^6$ (m ³ /Month)	$EWS \times 10^6$ (m ³ /Year)	x	Q_{tot} (MJ/m ² /Day)	E'_{FPV} (mm/Day)	$EWS \times 10^6$ (m ³ /Month)	$EWS \times 10^6$ (m ³ /Year)	
January	0.5	8.106	1.591	381.297	-	0.4	9.3465	1.999	314.833	-	
February	0.5	9.384	1.916	431.768	-	0.4	10.8633	2.422	357.422	-	
March	0.5	11.219	2.354	617.196	-	0.4	13.0443	2.997	512.487	-	
April	0.5	13.638	3.361	892.274	-	0.4	15.897	4.309	742.856	-	
May	0.5	15.178	3.590	1017.769	-	0.4	17.7406	4.628	848.894	-	
June	0.5	15.805	3.785	1049.224	-	0.4	18.4858	4.887	875.624	-	
July	0.5	15.548	3.742	1066.47	-	0.4	18.178	4.827	889.78	-	
August	0.5	14.970	3.743	1052.758	-	0.4	17.4803	4.819	877.695	-	
September	0.5	12.834	3.399	882.455	-	0.4	14.9249	4.343	733.733	-	
October	0.5	10.375	2.867	722.022	-	0.4	11.9933	3.628	598.058	-	
November	0.5	8.492	2.347	540.74	-	0.4	9.7572	2.947	446.279	-	
December	0.5	7.946	1.775	420.11	-	0.4	9.1399	2.226	346.591	-	
					9074.081						7544.251

Table 3. Water evaporation savings results (Case Study 3 and Case Study 4).

Months	Case Study 3					Case Study 4				
	x	Q_{tot} (MJ/m ² /Day)	E'_{FPV} (mm/Day)	$EWS \times 10^6$ (m ³ /Month)	$EWS \times 10^6$ (m ³ /Year)	x	Q_{tot} (MJ/m ² /Day)	E'_{FPV} (mm/Day)	$EWS \times 10^6$ (m ³ /Month)	$EWS \times 10^6$ (m ³ /Year)
January	0.3	10.587	2.437	243.472	-	0.2	11.828	2.906	167.212	-
February	0.3	12.342	2.969	277.072	-	0.2	13.821	3.556	190.718	-
March	0.3	14.87	3.698	398.413	-	0.2	16.696	4.456	274.974	-
April	0.3	18.156	5.350	578.919	-	0.2	20.415	6.483	400.465	-
May	0.3	20.303	5.772	662.68	-	0.2	22.866	7.023	459.126	-
June	0.3	21.166	6.105	683.902	-	0.2	23.846	7.437	474.057	-
July	0.3	20.808	6.025	694.788	-	0.2	23.438	7.336	481.494	-
August	0.3	19.991	6.003	684.887	-	0.2	22.501	7.297	474.335	-
September	0.3	17.015	5.376	571.127	-	0.2	19.106	6.496	394.636	-
October	0.3	13.611	4.453	463.873	-	0.2	15.229	5.3399	319.469	-
November	0.3	11.023	3.5899	344.974	-	0.2	12.288	4.277	236.827	-
December	0.3	10.334	2.710	267.821	-	0.2	11.529	3.227	183.799	-
					5871.927					4057.111

Figure 5 presents the average daily evaporation in each month for Lake Nasser, Aswan, Egypt (22°25' N 31°45' E) for the cases with and without FPV panels. As is evident in Figure 5, as well as in Table 1, if Lake Nasser was not covered by floating photovoltaic panels, the average daily evaporation during the months of the year ranged between 3.933 and 10.447 mm/day. This large discrepancy in the average daily evaporation during the months of the year is mainly due to the effect of climatic changes throughout the year. As shown in Figure 5 as well as Tables 2 and 3, when 50% of the Lake Nasser surface area was covered with floating photovoltaic panels, the average daily evaporation from Lake Nasser was reduced and ranged between 1.591 and 3.785 mm/day. Furthermore, when 40% of the Lake Nasser surface area was covered with floating photovoltaic panels, the average daily evaporation from Lake Nasser was reduced and ranged between 1.999 and 4.887 mm/day. When 30% of the Lake Nasser surface area was covered with floating photovoltaic panels, the average daily evaporation from Lake Nasser was reduced and ranged between 2.437 and 6.105 mm/day. Finally, when 20% of the Lake Nasser surface area was covered with floating photovoltaic panels, the average daily evaporation from Lake Nasser was reduced and ranged between 2.906 and 7.437 mm/day.

**Figure 5.** Average daily evaporation for each month throughout the year for the cases with and without FPV panels.

Figures 6 and 7 show the savings in surface evaporation (mm/day) and volume of evaporation water savings (m^3/day) that resulted from the installation of floating PV panels in Lake Nasser during the months of the year. The rates of savings in surface evaporation depended on the percentage of the area covered by the FPV panels. It is clear from the results presented in Figures 6 and 7 that for the case of covering 50% of the area of Lake Nasser with floating photovoltaic panels (Case Study 1), the savings in surface evaporation ranged between 2.343 and 6.662 mm/day ($12,299,915\text{--}34,974,125 \text{ m}^3/\text{day}$) throughout the year; for the case of covering 40% of the area of Lake Nasser (Case Study 2), the savings in surface evaporation ranged between 1.934 and 5.56 mm/day ($10,155,915\text{--}29,187,464 \text{ m}^3/\text{day}$) throughout the year; for the case of covering 30% of the area of Lake Nasser (Case Study 3), the savings in surface evaporation ranged between 1.496 and 4.342 mm/day ($7,853,921\text{--}22,796,718 \text{ m}^3/\text{day}$) throughout the year; and for the case of covering 20% of the area of Lake Nasser (Case Study 4), the savings in surface evaporation ranged between 1.027 and 2.958 mm/day ($5,393,939\text{--}15,801,891 \text{ m}^3/\text{day}$) throughout the year. These discrepancies in the savings values in surface evaporation for each of the four cases proposed were due to changes in weather conditions throughout the year.

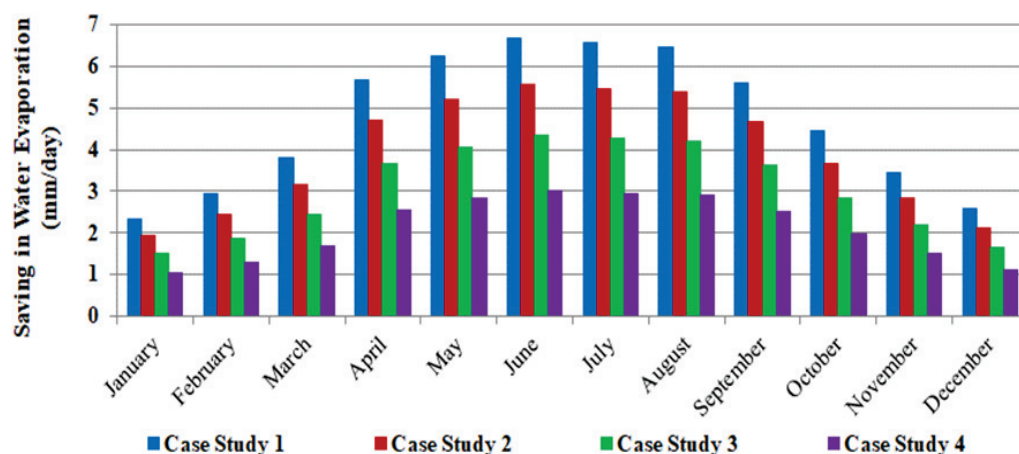


Figure 6. Average daily evaporation savings for each month of the year during the installation of FPV panels on Lake Nasser.

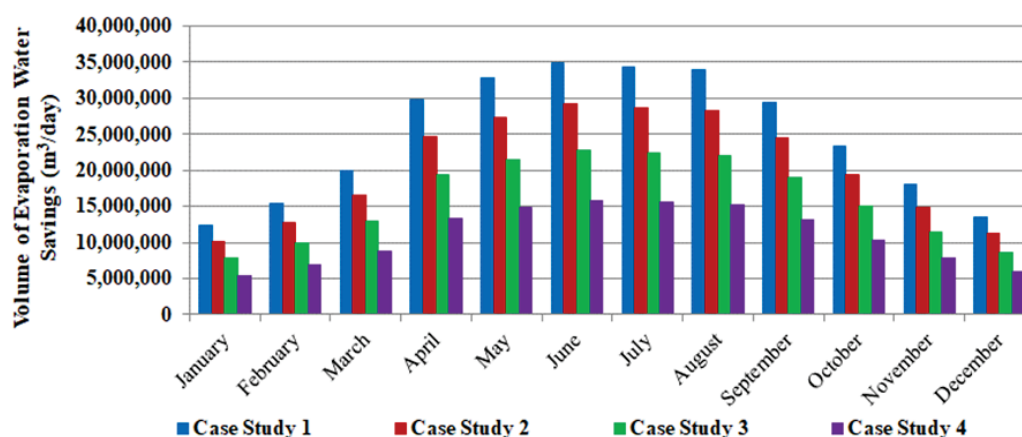


Figure 7. Average volume of daily water evaporation savings for each month of the year during the installation of FPV panels on Lake Nasser.

The results presented in Figures 5–7 and Tables 1–3 concluded that the installation of FPV panels in Lake Nasser represents a very effective proposal, especially for Egypt which suffers from water poverty for agriculture, domestic use and drinking. In addition, the construction of the Renaissance Dam currently being built in Ethiopia has caused

tensions between Egypt, Sudan, and Ethiopia. The rate of water evaporation savings in Lake Nasser reached 61.71% (9,074,081,000 m³/year) when covering 50% of the area of Lake Nasser with floating photovoltaic panels (Case Study 1). When covering 40% of the area of Lake Nasser (Case Study 2), the savings in water evaporation in Lake Nasser reached 51.24% (7,544,251,000 m³/year). The rate of water evaporation savings in Lake Nasser reached 39.83% (5,871,927,000 m³/year) when covering 30% of the area of Lake Nasser (Case Study 3), and the rate of water evaporation savings in Lake Nasser reached 27.49% (4,057,111,000 m³/year) when covering 20% of the Lake Nasser area with floating photovoltaic panels (Case Study 4).

3.2. Installed Capacity and Electricity Output of FPV Array

Figure 8 and Table 4 show the daily and annual electricity rates expected to be generated from the FPV panels system on the surface of Lake Nasser for the four cases proposed in this study, according to the climatic conditions of Aswan, Egypt. As shown in Figure 8, the daily rates of electricity expected to be generated from the FPV panels system for the four cases proposed in this study changed throughout the year as a result of changing climatic conditions. The daily rates of electricity production ranged between 877.9 and 1666.5 GWh/day when covering 50% of Lake Nasser with floating photovoltaic panels (Case Study 1). With 40% of Lake Nasser covered by floating photovoltaic panels (Case Study 2), the daily rates of electricity production range between 702.3 and 1333.2 GWh/day. The daily rates of electricity production ranged between 526.8 and 999.9 GWh/day when covering 30% of Lake Nasser with floating photovoltaic panels (Case Study 3). Lastly, with 20% of Lake Nasser covered with floating photovoltaic panels (Case Study 4), the daily rates of electricity production ranged between 351.2 and 666.6 GWh/day.

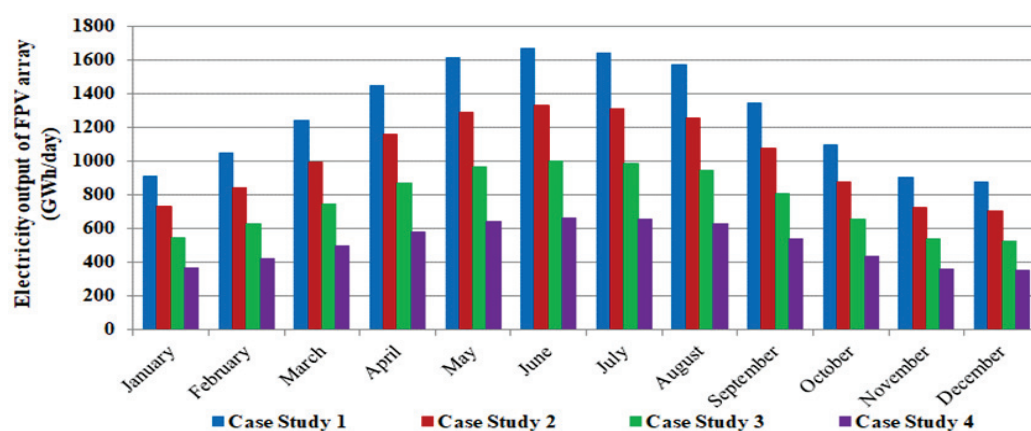


Figure 8. Daily electricity generation of a floating photovoltaic array installed on Lake Nasser.

The results presented previously showed that covering Lake Nasser with floating photovoltaic panels represents a very effective solution for Egypt, which suffers from water poverty in addition to electric power. As shown in Table 4, the annual rates of electricity production from the floating photovoltaic system of Lake Nasser depended on the percentage of the area covered by the floating photovoltaic panels. The annual rate of electricity production from the FPV panels system for Lake Nasser reached 467.99 TWh/year, 374.41 TWh/year, 280.787 TWh/year, and 187.21 TWh/year when covering 50% (Case Study 1), 40% (Case Study 2), 30% (Case Study 3), and 20% (Case Study 4) of Lake Nasser with FPV panels, respectively.

Table 4. Floating photovoltaic (FPV) panels generation results.

Months	A_{res} (km ²)	Case Study 1			Case Study 2			Case Study 3			Case Study 4		
		x	FPVep (TWh/ Month)	FPVep (TWh/ Year)	x	FPVep (TWh/ Month)	FPVep (TWh/ Year)	x	FPVep (TWh/ Month)	FPVep (TWh/ Year)	x	FPVep (TWh/ Month)	FPVep (TWh/ Year)
January	5250	0.5	28.32	-	0.4	22.67	-	0.3	16.99	-	0.2	11.33	-
February	5250	0.5	29.42	-	0.4	23.53	-	0.3	17.65	-	0.2	11.77	-
March	5250	0.5	38.57	-	0.4	30.86	-	0.3	23.14	-	0.2	15.43	-
April	5250	0.5	43.46	-	0.4	34.77	-	0.3	26.08	-	0.2	17.39	-
May	5250	0.5	49.96	-	0.4	39.97	-	0.3	29.97	-	0.2	19.98	-
June	5250	0.5	50	-	0.4	40	-	0.3	30	-	0.2	20	-
July	5250	0.5	50.85	-	0.4	40.68	-	0.3	30.51	-	0.2	20.34	-
August	5250	0.5	48.7	-	0.4	38.96	-	0.3	29.22	-	0.2	19.48	-
September	5250	0.5	40.44	-	0.4	32.35	-	0.3	24.26	-	0.2	16.18	-
October	5250	0.5	33.96	-	0.4	27.17	-	0.3	20.377	-	0.2	13.58	-
November	5250	0.5	27.09	-	0.4	21.68	-	0.3	16.26	-	0.2	10.84	-
December	5250	0.5	27.22	-	0.4	21.77	-	0.3	16.33	-	0.2	10.89	-
		467.99			374.41			280.787			187.21		

4. Conclusions

Floating solar photovoltaic panels are an advanced technology that aims to reduce the rates of water evaporation from water bodies to reduce the problem of water shortages that most countries of the world suffer from, in addition to generating electricity while at the same time eliminating the need to use valuable land. At the global level, we find that irrigation ponds contain nearly 70% of freshwater resources, and this percentage rises to 90% for remote areas. Lake Nasser (the lake of the High Dam) is considered one of the largest artificial lakes in the world, and it is located in southern Egypt, south of Aswan (22°25' N 31°45' E), with an estimated area of about 5250 square kilometers. Egypt is among the countries that suffer from water poverty and this problem will be exacerbated in the future due to Ethiopia's construction of the Renaissance Dam, which has led to strained relations between Egypt, Sudan, and Ethiopia. Therefore, the current study proposed the use of floating photovoltaic technology to partially cover Lake Nasser to reduce water evaporation rates and produce electricity. Covering Lake Nasser with floating photovoltaic cells can reduce water evaporation rates, helping to solve the problem of water poverty that Egypt suffers from. This paper dealt with four proposals to partially cover Lake Nasser with floating photovoltaic panels. In the first proposal, 50% of the area of Lake Nasser was covered by floating photovoltaic panels. In the second proposal, 40% of the area of Lake Nasser was covered by floating photovoltaic panels. In the third proposal, 30% of the area of Lake Nasser was covered by floating photovoltaic panels. In the fourth proposal, 20% of the area of Lake Nasser was covered with floating photovoltaic panels. Among the most important results reached are the following:

- The installation of FPV panels on Lake Nasser is a very effective solution for Egypt which suffers from water poverty, as the rate of water evaporation savings in Lake Nasser reached 61.71% (9,074 081, 000 m³/year) when covering 50% of Lake Nasser area with floating photovoltaic panels.
- The rate of water evaporation savings in Lake Nasser depends on the percentage of the area covered by the floating photovoltaic panels, which reached 61.71%, 51.24%, 39.83%, and 27.49% for covering 50%, 40%, 30%, and 20% of the area of Lake Nasser with FPV panels, respectively, as compared to the conventional case without FPV panels.
- The annual rate of electricity production from the FPV panels system for Lake Nasser reached 467.99 TWh/year, 374.41 TWh/year, 280.787 TWh/year, and 187.21 TWh/year for covering 50%, 40%, 30%, and 20% of Lake Nasser with FPV panels, respectively.

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Article

Simultaneous Removal of Metal Ions from Wastewater by a Greener Approach

Lubna A. Ibrahim ^{1,2,*}, Marwa E. El-Sesy ², ElSayed ElBastamy ElSayed ², Martina Zelenakova ^{3,*}, Maria Hlinkova ⁴, Essam Sh. Mohamed ⁵ and Mohamed Abu-Hashim ⁶

¹ Water Management Research Institute (WMRI), National Water Research Center (NWRC), El-Qanater El-Khairia 13621, Egypt

² Central Laboratory for Environmental Quality Monitoring, National Water Research Center (NWRC), El-Qanater El-Khairia 13621, Egypt

³ Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Kosice, 04200 Kosice, Slovakia

⁴ Faculty of Civil Engineering, Institute of Technology, Economics and Management in Construction, Technical University of Kosice, 04200 Kosice, Slovakia

⁵ Institute of Global Health and Human Ecology, The American University in Cairo, New Cairo 11835, Egypt

⁶ Soil Science Department, Faculty of Agriculture, Zagazig University, Zagazig 44511, Egypt

* Correspondence: lubnaibrahim43@gmail.com (L.A.I.); martina.zelenakova@tuke.sk (M.Z.)

Abstract: The examination of the performance of raw and immobilized *S. (Saccharomyces) cerevisiae* in the simultaneous abatement of metal ions from wastewater effluent is the focal point of this article. The optimal storage time for raw and immobilized *S. cerevisiae*, during which they can be utilized, was estimated. The outcomes revealed that as the initial metal ion concentrations increased, the adsorption capacity improved, while the removal efficiency of *S. cerevisiae* yeast cells decreased, with the highest uptake obtained at the optimal conditions: pH = 5.0, 2.0 g *S. cerevisiae*/L, 25 °C, and a contact time of 25 min. The maximum adsorption capacities ($q_{\max}$) for Pb(II), Cd(II), and Ni(II) ions are shown by Langmuir at 65, 90, and 51 mg/g, respectively. It was discovered that the metal ions' biosorption reactions were spontaneous and were fitted by the pseudo-second-order model. The mechanisms of the metal ions' abatement were explained by using XRD (X-ray diffraction), FTIR (Fourier transform infrared spectroscopy), (BET) Brunauer–Emmett–Teller, and TEM (transmission electron microscopy) outputs. EDTA and citric acid can eliminate more than 70 ± 4 and $90 \pm 5\%$ of the adsorbed ions, respectively. The experiment of storage demonstrated that the immobilized *S. cerevisiae* was more stable for 8 months than the raw yeast.

Keywords: fixed-bed column; immobilized *S. cerevisiae*; industrial wastewater treatment

1. Introduction

Climate change requires sustainable and innovative treatment approaches to deal with the quickly depleting water resources that have rendered water a competitive resource for many regions globally. Producing stable materials through low-cost approaches to provide adequate amounts of freshwater is the need of the water industry that has motivated many scientists and researchers to research nontraditional water treatment techniques to increase the quantity of water. Fast urbanization and industrialization in the world have prompted the introduction of heavy metals by industrial and mining activities: manure, paints, battery manufacture, and spillage of industrial wastes, plus pesticide-based metals [1]. Among the metal ions, lead (Pb(II)), cadmium (Cd(II)), and nickel (Ni(II)) ions are perceived to be huge ecological pollutants [2].

Several physicochemical treatment methods (precipitation, coagulation–flocculation, membrane processes, chemical precipitation, ion exchange, electrodeposition, and electrochemical techniques) have demonstrated adequate performance in the abatement of trace

elements from aqueous solutions [3–6] but remain economically nonviable because of the additional capital, unpredictable efficiency, generation of toxic sludge, high energy and reagent requirements, and high operational costs that have diminished their possibilities for widespread use [7,8]. Electrodeposition, as opposed to adsorption and chemical precipitation, is a more cost-effective and safe method of removing and recovering heavy metals from wastewater that does not require the utilization of chemicals [9,10]. Adsorption, in any case, remains a feasible alternative, particularly in developing nations, since it is environmentally benign, simple, inexpensive, and does not produce large sludge quantities [11,12]. In recent decades, various natural and manufactured adsorbents have been examined for their ability to eliminate heavy metals from contaminated solutions [13–20]; however, separating these adsorbents from the aqueous solution entails a complex process with additional costs, and structure stability should be emphasized [20].

Biosorption is a significantly more proficient strategy for the elimination of numerous pollutants, which include heavy metals, because of the accessibility of a diverse range of biosorbents that have low prices and adapt to various circumstances [21–24]. In this way, different sorts of microorganisms (bacteria, yeasts, algae, fungi) [25–27] have affirmed that they can recover heavy metals from aqueous solutions via biosorption [7,27–29]. *Saccharomyces cerevisiae* (*S. cerevisiae*) yeast is generally utilized in food biotechnology processes, such as the production of wine, bread, and beer. It is an especially appropriate organism for biological examinations and it has “generally regarded as safe (GRAS) status” [30]. Thus, efficient and low-cost processes for producing large-scale yeast biomass have evolved. *S. cerevisiae* is a promising biosorbent that has been shown to eliminate pesticides [31], mycotoxins [32], and trace elements from synthesized water or aqueous solutions, even when deactivated, and it has its highest efficiency in short contact times [7,29,33–45]. Furthermore, the encapsulation of *S. cerevisiae* in a biopolymer, for example, alginate [32,43,46–50], is an alternative strategy for their application, as well as being steadier, simple-to-deal with, and economical.

Hence, in this examination, the performance of *S. cerevisiae* (grown on Yeast Peptone Dextrose (YPD)) biomass at 25 °C for ions being rid from the water was assessed. The influence of pH, *S. cerevisiae* dose, initial metal ion concentration in solution, contact time, and temperature on ion biosorption efficiency and biosorption capacity of the biomass was examined. The equilibrium data have also been examined via isotherm, kinetic, and thermodynamic investigations. The biosorption mechanism of *S. cerevisiae* was explained by considering the XRD, FTIR, BET, and TEM techniques. The adequacy of different eluents (H_2O , NH_4NO_3 , $EDTA-Na_2$, and citric acid) to desorb or regenerate the biosorbed metal ions was also examined. At last, the efficacy of *S. cerevisiae* and the fixed-based column (immobilized *S. cerevisiae*) for the abatement of metal ions from wastewater were compared and the best storage time after which they could be reused was determined. Outcomes verified the capacity of *S. cerevisiae* in the biosorption of mono-components from synthesized water and comparison of two approaches for the take-up of metal ions from real wastewater samples. The outcome of this investigation would be to provide eco-friendly metal ion abatement materials, stable for 8 months (m), mostly from wastewater of different multi-components.

2. Experimental

2.1. Wastewater Sampling

Screw-capped sterilized bottles were utilized for the collection of wastewater samples from “Al-Monairy for corn products, Madinat al-Āshir min Ramadān, As Sharqia, Egypt”. The fundamental products of that factory are corn (starch, flour, and grits), glucose, fructose, gluten (corn and feed), high maltose, dextrose, and maize oil that are widely used in most other manufacturing industries (i.e., pharmaceuticals, textile, paper, food products and feed). The color of gathered samples was black and specified by their high content of solids.

2.2. Reagent, Biosorbent, Media, Culture Condition, and Drying Process

All chemicals and supplements were of high-purity analytical grade. For aqueous solution preparation and cleaning purposes, double-deionized water (DDW) was utilized. Calcium chloride (95+% CaCl_2) was purchased from Chem-Lab NV (made in Belgium), while sodium alginate (91–106% $\text{C}_8\text{H}_7\text{O}_8\text{Na}$) was a Techno PharmChem product. YPD Broth was Merck (KGaA—Bioz) product. Ammonium nitrate (>99%, NH_4NO_3), citric acid (>99%, $[\text{HOC}(\text{COOH})(\text{CH}_2\text{COOH})_2]$), and Ethylenediaminetetraacetic acid disodium salt solution (0.5 M EDTA- Na_2 in H_2O) were purchased from Sigma-Aldrich. *S. cerevisiae* culture was acquired from the Microbial products lab of the “National Research Center (NRC)/Egypt”.

Then *S. cerevisiae* was cultured on sterilized Yeast Peptone Dextrose (YPD) agar broth at 25 ± 1 °C and then kept up at 4 °C on YPD agar slant. The media was prepared to comprise (w/v %): glucose, 2%; yeast extract, 1%; peptone, 2%, and agar, 2%. Each strain was cultured at 25 ± 1 °C for 24 h at 150 rpm in sterilized media (YPD) and the cells were collected for that investigation. Strains were kept at -4 ± 1 °C until they were utilized in the trials [46,47]. After culturing, *S. cerevisiae* yeast cells were harvested by centrifugation at 6000 rpm for nine min. The harvest cells were rinsed with DDW few times to eliminate excess growth medium before being centrifuged. The *S. cerevisiae* yeast was dried in an autoclave at 25 ± 1 °C until constant weight, homogenized, and saved in a desiccator until use.

2.3. Biosorption Parameters Investigation

For each investigated metal ion, all the examinations were performed by suspending the biosorbent in solution by varying the parameters: pH (2–8), ion concentration (25–250 mg/L), biosorbent dose (2–16 g/L), contact time (6–180 min), and temperature (15–40 °C), while the others stayed constant. The solution was incubated at 20 °C on a rotary shaker (150 rpm) for 2 h. The filtrate was centrifuged at $6000 \times g$ for nine min and then filtered utilizing 0.45 μm pore size filter paper to eliminate particle intrusion into the analytical equipment. The initial (C_i) and equilibrium final (C_e) concentrations of investigated metal ions were quantified (mg/L). Each trial had three repetitions, the results were averaged, and the standard deviation (STD) was calculated. The removal efficiency (RE%) and the adsorption capacity (q_e , mg/g) were estimated by Equations (1) and (2), in which V is the volume (L) of the solution, and W is the mass (g) of biosorbent [18,51].

$$\text{Removal Efficiency (RE\%)} = \frac{C_i - C_e}{C_i} \times 100 \quad (1)$$

$$q_e = (C_i - C_e) \frac{V}{W} \quad (2)$$

2.4. Laboratory Water Analyses

All examinations were conducted in an ISO 17025: 2017 certified laboratory of the “Central Laboratory for Environmental Quality Monitoring (CLEQM)”. The samples were subjected quickly to physical and chemical examinations as demonstrated by the Standard Methods for the Examination of Water and Wastewater [52]. The pH, electric conductivity (EC), and dissolved oxygen (DO) were estimated at 25 °C utilizing a pH meter InoLab WTW, conductivity meter InoLab, and DO meter, respectively. Trace metals and cations were estimated utilizing the ICP-MS, PerkinElmer product model SCIEX Elan 9000. Recovery studies for the investigated metal ions analyzed utilizing ICP-MS ranged from 98 to 102%.

2.5. Biosorption Isotherm, Kinetics, and Thermodynamics Studies

Two isotherm models (Langmuir and Freundlich), three kinetics models (pseudo-first-order (1st), pseudo-second-order (2nd), and intraparticle diffusion), and thermodynamic parameters were utilized to model the empirical data using the mathematical formulas [29,34,47]

prescribed in Table 1. The best isotherm and kinetics models were selected relying on the regression coefficients (R^2), estimated statistically.

Table 1. Mathematical equations of both isotherm and kinetic models, and thermodynamics parameters utilized for the empirical data analysis.

	Model	Equation	Notations
Isotherm models	Langmuir	$\frac{C_e}{q_e} = \frac{1}{q_{\max}} K_d + \frac{C_e}{q_{\max}}$	where C_e is the equilibrium (final) metal ions concentration (mg/L), K_d is an apparent dissociation constant, n indicates the intensity of the process, $q_{\max}$ represents the capacity for metal ion uptake when the surface is completely covered with metal ions, K_f is a biosorption equilibrium constant, q_e and q_t (mg/g) are the amounts of Cd(II), Pb(II), and Ni(II) ions adsorbed on the adsorbent at equilibrium and time t (min), respectively. I is the intercept and k_1 (1/min), k_2 (g/mg min), v_1 (g/mg min), and K_d (mg/g min ^{0.5}) are the rate constant of pseudo-1st-order, pseudo-2nd-order, initial sorption rate, and intraparticle diffusion, respectively.
	Freundlich	$\ln q_e = \ln K_f + \frac{1}{n} \ln C_e$	
Kinetic models	Pseudo-first (1st)-order	$\log(q_e - q_t) = \log q_e - \left(\frac{k_1}{2.303}\right) \cdot t$	
	Pseudo-second (2nd)-order	$\frac{t}{q_t} = \frac{1}{v_1} + \frac{t}{q_e}$ $v_1 = k_2 q_e^2$	
	Intraparticle diffusion	$q_t = K_d t^{0.5} + I$	
Thermodynamic	Thermodynamic parameters	$-\Delta G^0 = -RT \ln K_D$ $\ln K = \frac{\Delta H^0}{RT} + \frac{\Delta S^0}{R}$ $\Delta G^0 = \Delta H^0 - T\Delta S^0$	ΔG^0 , ΔH^0 , and ΔS^0 are the free energy change, enthalpy changes, and entropy change, respectively. R (8.314 J/mol K) is the universal gas constant, T is the absolute temperature (K), and K is the equilibrium constant.

2.6. Characterization Techniques

X-ray diffraction patterns (XRD) of powder samples of *S. cerevisiae* and Pb(II)-biosorbed *S. cerevisiae* biomass were registered in a Broker D8 Advanced target CuK α powder diffractometer ($\lambda = 1.5418 \text{ \AA}$) over the range of $2\theta = 0\text{--}80^\circ$ scale. FTIR for *S. cerevisiae* and uploaded Pb(II) was examined in KBr discs containing about 3% (w/w) of finely ground powder of each sample using spectrophotometer PerkinElmer FTIR 1650 in El-Zagazig University. For treated *S. cerevisiae* and uploaded Pb(II): the surface area analysis, average particle size, and total pore volume were obtained by utilizing the Brunauer–Emmett–Teller (BET, HitachiVP-SEM S-3400N, Germany) method. The TEM for *S. cerevisiae* and uploaded Pb(II) was performed utilizing JEOL TEM-1400 electron microscope and optronics AMT CCD camera with 1632 pixel format as side mount configuration relying on the strategies applied by El-Sayed [48].

2.7. Yeast Cell Immobilization and Its Application for Simultaneous Treatment of Wastewater

The immobilization procedures were carried out in accordance with the procedure reported in Araujo et al. [49] (Figure 1). For biosorption fixed-bed column, a glass column (height 2.5 cm, inner diameter 0.38 cm) was packed with 2 g of calcium alginate beads loaded with *S. cerevisiae* [49,50]. During the treatment, the column temperature was kept constant at 25 °C. One liter (L) of the sample (pH 5.0) was pumped through the column at 1.5 mL/min for 25 min contact time. After a resident time, the samples were gathered and analyzed immediately as described before.



Figure 1. Immobilized *S. cerevisiae*.

2.8. Desorption Experiments from Loaded Cell Biosorbent

Desorption of Cd(II), nickel (Ni(II)), and lead (Pb(II)) from previously loaded resting immobilized cells was examined by utilizing deionized water (H₂O), 1.0 mol/L of NH₄NO₃, 0.1 mol/L of EDTA-Na₂, and 10% citric acid as eluents. The trials were tested with 0.036 g Cd(II)-, 0.034 g nickel (Ni(II))- , and 0.046 g lead (Pb(II))-loaded 1 g immobilized cell biosorbent in 50 mL plastic tubes containing 20 mL of each eluent. After 30 min of shaking at 25 °C, supernatants were centrifuged and analyzed for metal ions by ICP-MS. Adsorption capacities for each of the recently mentioned eluents were assessed by the amount of metal ion concentrations in the desorption solution. Sequential sorption–desorption cycles were repeated thrice trials to lay out the reutilizing of the adsorbent. In the meantime, biosorption capacity was also assessed.

2.9. Storage of the Yeast Cells

The free and immobilized *S. cerevisiae* was kept in a refrigerator at 4 ± 1 °C in saline solution for 0 months (m), 2 m, 4 m, and 8 m, and then utilized for treating the collected wastewater samples.

2.10. Statistical Analyses

Data were exposed to investigation utilizing statistical software IBM® SPSS®, V 26, 2019, and reported as min, max, mean values, and standard deviation (SD). The statistical programs SPSS and Costat (V. 6.400, USA) were utilized to recognize and compare treatments utilizing analysis of variance (ANOVA) and multiple component tests.

3. Results and Discussion

3.1. Optimum Conditions and Modeling Biosorption Processes by *S. cerevisiae*

3.1.1. Impact of pH on Biosorption Capacity

pH is the most critical consideration in the biosorption process. It impacts the competition of metal ions and the activity of the biomass functional groups [29,53]. The adsorption of different metal ions on *S. cerevisiae* was examined at pH values of 2, 3, 4, 5, 6, 7, and 8 to optimize the progression of the Cd(II), Pb(II), and Ni(II) removal rates with pH as shown in Figure 2A. The sorption capacity of the ions increases as the pH of the aqueous solution rises from 2 to 5 due to the protons preferentially binding to the superficial functional groups [29]. Then the capacity decreases as pH rises from 6 to 8 because of the –OH[−] group competing with the binding sites on the *S. cerevisiae* cell wall to combine with metal ions and precipitate as metal complexes Cd(OH)₂, Ni(OH)₂, and Pb(OH)₂; thus, it is not able to bind to the functional groups present in or on the cell wall [36]. Considering these outcomes, the biosorption of the examined metal ions on the *S. cerevisiae* biomass happens with the highest efficacy at a pH of 5, and this value was the most suitable and was utilized in all other experimental studies.

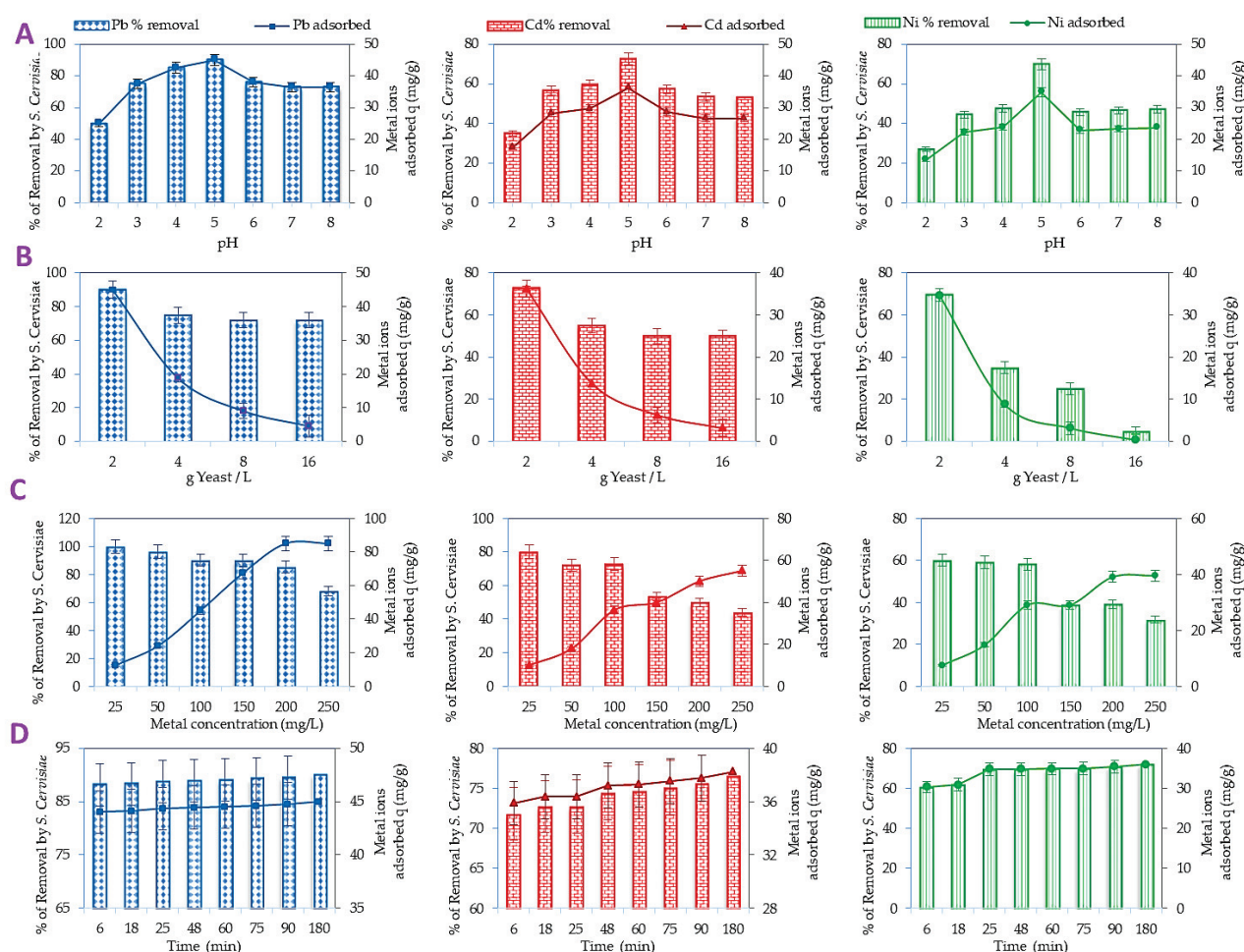


Figure 2. Impact of pH (A), biosorbent dose (B), initial concentration (C), and (D) time on the removal efficiency and adsorption capacity of Cd(II), Pb(II), and Ni(II) ions on *S. cerevisiae* yeast cells. For (A,B,D) the biosorbent concentration was 0.5 g/250 mL (dry mass/volume), and the initial metal concentration 100 mg/L, 25 °C, 150 rpm and 2 h. Error bars represent standard deviation.

3.1.2. Impact of Biosorbent Dose

The influence of various biomass (*S. cerevisiae*) doses on the biosorption performance for Cd(II), Pb(II), and Ni(II) was investigated and is delineated in Figure 2B. It can be seen from Figure 2B that the biosorption capacity is greatest at a biosorbent dosage of 2 g/L. As the biosorbent dose increased, the biosorption capacity reduced, while the efficacy of biosorption increased. The variation in biosorption processes is explained by the lessening in the ratio among the number of ions and the number of biosorbent functional groups [54]. Furthermore, raising the biosorbent dosage to 2–4 g/L results in a negligible advancement (up to 10%) in the metal ions' removal percentage. Hence, a dosage of 2 g/L was sufficient for the biosorption of the investigated metal ions on *S. cerevisiae* and was deemed optimal.

3.1.3. Impact of Initial Concentration and Biosorption Isotherms

Figure 2C displays the efficiency of *S. cerevisiae* as an adsorbent for each metal ion in adsorption experiments at concentrations ranging from 25 to 250 mg/L. The outcomes demonstrated that the capacity of biosorption (removal ratio) enhances, while the biosorption yield of biomass reduces as the initial metal ions' concentration increases. While the pathway of biosorption of the investigated metal ions is reliant on their initial concentration, at low concentrations, metal ions are biosorbed by specific active sites on *S. cerevisiae*, while with increasing metal ion concentrations, the specific sites are somewhat saturated. Our results were reinforced by the investigation of Martins et al. [55] in which they exhibited

that the adsorption rate significantly reduced with increasing elemental Cd(II), Pb(II), and Ni(II) concentrations up to 100 mg/L.

Linear Langmuir and Freundlich biosorption isothermal models for the trace elements investigated by *S. cerevisiae* are exhibited in Figure 3A,B, respectively. Table 2 shows the model parameters (K_d , $q_{\max}$, K_f , and n) estimated from the experimental and model isotherms for investigated metal ions. Langmuir isotherms provide the best fit for the computed values for *S. cerevisiae*; that conclusion can be based on a high R^2 correlation coefficient ($R^2 \geq 0.99$) compared to the R^2 of another isotherm ($R^2 = 0.96$ – 0.98). During the adsorption process, the investigated ions cover the adsorbent with monolayer sorption onto a surface with a finite number of matching sorption sites.

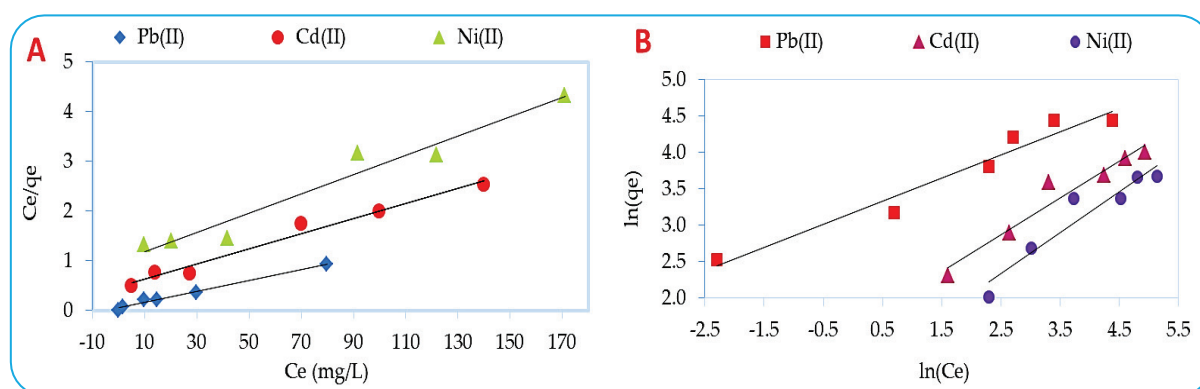


Figure 3. (A) Langmuir and (B) Freundlich biosorption isotherms of Cd(II), Pb(II), and Ni(II) by *S. cerevisiae*.

Table 2. Isotherm Model Parameters for Adsorption of Cd(II), Pb(II), and Ni(II) on *S. cerevisiae* using Langmuir and Freundlich Isotherms.

Parameters	Langmuir Model				Freundlich Model		
	$q_{\max}$ (mg/g)	$b = (1/K_d)$	R^2	RL	K_f (L/g)	n	R^2
Cd(II)	65.36	0.032	0.98	0.11–0.56	4.95	1.98	0.94
Pb(II)	90.09	0.193	0.99	0.02–0.17	23.69	3.14	0.94
Ni(II)	51.55	0.020	0.95	0.17–0.67	2.50	1.77	0.90

The highest biosorption capacity ($q_{\max}$) for Cd(II), Pb(II), and Ni(II) ions is 65, 90, and 51 mg/g, respectively. The fundamental isothermal characteristics of Langmuir's are evident in expressions of RL (a dimensionless constant separation factor), known as $RL = \frac{1}{(1+bC_0)}$ in the range $0 < RL < 1$, reflecting the appropriate adsorption process [56]. As indicated by the low RL values for lead (0.02–0.17) and the high RL values for nickel (0.67–0.17), the yeast cells showed a high and low affinity for Pb^{2+} and Ni^{2+} , respectively. However, the values of RL for any tested metal ion were found in the range $0 < RL < 1$, confirming that the adsorption process was suitable for the examined metal ions. In addition, the value of $1/n < 1$ calculated from the Freundlich isotherm model confirms that the process is chemical [57].

Table 3 presents a comparison of the $q_{\max}$ obtained from the Langmuir isotherm model in the literature data [33,42,47,58–62] with this investigation for various adsorbents to Cd(II), Pb(II), and Ni(II). The $q_{\max}$ value for Cd(II) was found to be 65.36, which was higher than that of *B. thuringiensis*-remediated wastewater [58], ethanol-treated yeast [47], and EDTA-treated yeast [60]. The $q_{\max}$ value was found to be 90.09 mg/g for Pb(II), which was higher than that of *P. chrysosporium*-treated wastewater [59], a bioreactor biosorption system [42], and ethanol-treated *S. cerevisiae* [47], but less than that of EDTA-treated yeast [60]. The $q_{\max}$ was estimated to be 51.55 mg/g for Ni(II), which was near the value estimated by Guler

and Ersan [61], and was higher the value Özer and Özer [33] and Guler and Sarioglu [62]. The $q_{\max}$ for the prepared yeast was higher and lower, respectively, than the $q_{\max}$ found in the literature, probably attributed to the condition of the reaction, the treatment materials, the source of yeast, the media used to culture the yeast, and the inactivation. All of the above confirmed that culturing yeast on YPD and drying it at 25 °C enhanced its properties more than the studies in the literature for the biosorption of Cd(II) Pb(II), and Ni(II) ions.

Table 3. The maximum adsorption capacity ($q_{\max}$) of various biosorption capacities of biomass discovered in this research was compared to those published in the literature for Cd(II), Pb(II), and Ni(II), respectively.

Metal Ions	Biomass	$q_{\max}$ (mg/g)	Reference
Cd(II)	<i>B. thuringiensis</i>	59.17	[58]
	<i>S. cerevisiae</i>	31.75	[47]
	<i>P. chrysosporium</i>	27.79	[59]
	<i>S. cerevisiae</i>	32.26	[60]
	<i>S. cerevisiae</i>	65.36	This study
Pb(II)	<i>S. cerevisiae</i>	72.46	[42]
	<i>B. thuringiensis</i>	30.76	[58]
	<i>P. chrysosporium</i>	85.57	[59]
	<i>S. cerevisiae</i>	60.24	[47]
	EDTA-treated <i>S. cerevisiae</i>	200	[60]
	<i>S. cerevisiae</i>	90.09	This study
Ni(II)	<i>S. cerevisiae</i> nZVI	54.23	[61]
	<i>S. cerevisiae</i>	21.39	[62]
	<i>S. cerevisiae</i>	46.30	[33]
	<i>S. cerevisiae</i>	51.55	This study

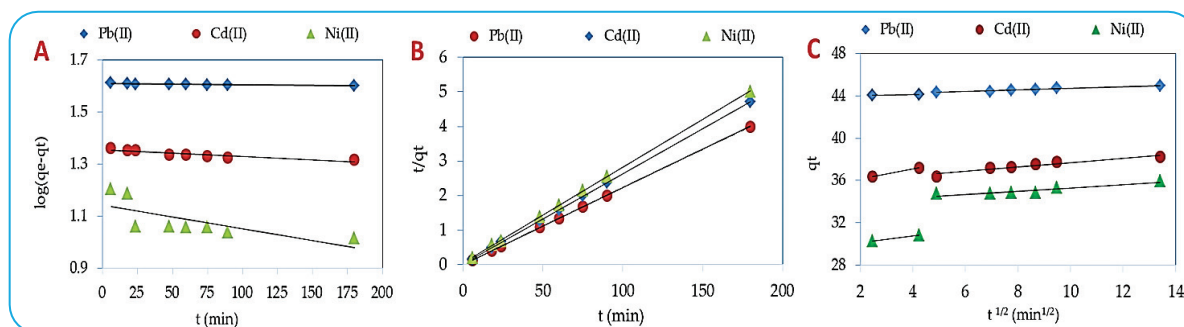
3.1.4. Impact of Time on Biosorption and Kinetic Isotherms

The consequence of the biosorption kinetics of Cd(II), Pb(II), and Cu(II) ions at various intervals time for *S. cerevisiae* is shown in Figure 2D. In the range of 6 min and 18 min, the ions are rapidly biosorbed by the *S. cerevisiae*, and the state of equilibrium arrives at 25 min for the examined metal ion. Those returning to the functional groups of *S. cerevisiae* are uncovered, and the metal ions are rapidly bound, regardless of their nature. After 48 min, there was no further increase in biomass biosorption capacity for ions, and the removal percentage did not change significantly until 180 min. This implies that the entire surface of the *S. cerevisiae* was coated. Hence, metal ions struggle to identify active centers accessible for binding, resulting in a slow increase in biosorption capacity. Thusly, a contact time of 25 min is adequate to attain equilibrium in the case of the biosorption of the three examined metal ions on *S. cerevisiae*.

The regression coefficient (R^2) values clarified that the pseudo-second order (2nd) model, ($R^2 > 0.99$ –1.00) was the best-fitting model compared with pseudo-first-order rate kinetics ($R^2 > 0.54$ –88), and the intraparticle diffusion model ($R^2 > 0.85$ –0.96), see Table 4 and Figure 4A–C. The rate constant of the pseudo-second-order was in the range of 0.013–0.049 g/mg/min, see Table 4. These outcomes were supported by Amirnia et al. [42]. Thus, in this case, the limiting rate of the biosorption reaction may be chemisorption since the removal of the investigated metal ions occurs most often via surface complexation reactions at specific biosorption sites [63]. Thusly, the metal ions' retention on the surface of *S. cerevisiae* is accomplished via chemical interactions that include two active centers in good geometric positions. The proclivity of metal ions to cooperate with the binding sites of *S. cerevisiae*, depicted by k_2 , indicates that Pb(II) ions are most effectively retained (0.049 g/mg min), accompanied by Cd(II) ions (0.021 g/mg min), and finally Ni(II) ions (0.013 g/mg min).

Table 4. Kinetic parameters of the Cd(II), Pb(II), and Ni(II) removal by *S. cerevisiae* biomass.

Ions	Pseudo-First-Order			Pseudo-Second-Order				Intraparticle					
	q_e (mg/g)	K_1 (min ⁻¹)	R^2	v_2 (mg/gmin)	q_e (mg/g)	k_2 (g/mg min)	R^2	Zone I			Zone II		
								K_d (mg/g/min ^{0.5})	I	R^2	K_d (mg/g/min ^{0.5})	I	R^2
Pb(II)	40.9	0.0001	0.88	99.0	45.05	0.049	1.00	0.05	43.93	0.99	0.08	43.16	0.96
Cd(II)	22.8	0.0007	0.84	30.7	38.5	0.021	0.99	0.26	35.24	0.99	0.21	35.61	0.91
Ni(II)	13.9	0.0021	0.54	17.5	36.2	0.013	0.99	0.32	29.49	0.96	0.15	33.80	0.85

**Figure 4.** Plot of pseudo-first order equation (A), pseudo-second order equation (B), and intraparticle (C) of Cd(II), Pb(II), and Ni(II) ions' adsorption by *S. cerevisiae* biomass.

3.1.5. Impact of Temperature on Biosorption and Thermodynamic Studies

The thermodynamic parameters Gibbs free energy (ΔG°), enthalpy (ΔH°), and entropy (ΔS°) clarify how spontaneous the biosorption process is, see Table 5. The equilibrium constant (K) was estimated using the equation: $\Delta G = -RT \ln K$ at different temperatures (15–40 °C). The greatest biosorption capacity for the examined ions by *S. cerevisiae* was achieved at a temperature of 25 °C; after that, the %RE and the biosorption capacity were constant, see Figure 5A. The negative values of ΔG for the tested metal ions proved that the biosorption process was spontaneous. The ΔH° and ΔS° for the biosorbent were calculated utilizing the Van't Hoff plot of $\ln K$ against $1/T$, see Figure 5B. The positive values of the ΔS° for all trials of metal ions demonstrated an expansion in irregularity at the solid/liquid interface during the biosorption process. The negative values of ΔG° , while ΔS° had positive values, were supported by Gialamoudidis et al. [64]. The positive ΔH° for the trial metals revealed that the biosorption process was endothermic.

Table 5. Values estimated from the thermodynamic analysis.

Temperature T (K)	288	293	298	303	313
Pb(II)					
Gibbs free energy ΔG° (kJ mol ⁻¹)	−2.62	−2.99	−3.36	−3.73	−4.47
Entropy ΔS° (kJ mol ⁻¹ K ⁻¹)			0.073		
Enthalpy ΔH° (kJ mol ⁻¹)			18.64		
Cd(II)					
Gibbs free energy ΔG° (kJ mol ⁻¹)	−0.66	−0.96	−1.25	−1.55	−2.14
Entropy ΔS° (kJ mol ⁻¹ K ⁻¹)			0.059		
Enthalpy ΔH° (kJ mol ⁻¹)			16.39		
Ni(II)					
Gibbs free energy ΔG° (kJ mol ⁻¹)	−0.05	−0.33	−0.61	−0.89	−1.45
Entropy ΔS° (kJ mol ⁻¹ K ⁻¹)			0.056		
Enthalpy ΔH° (kJ mol ⁻¹)			16.16		

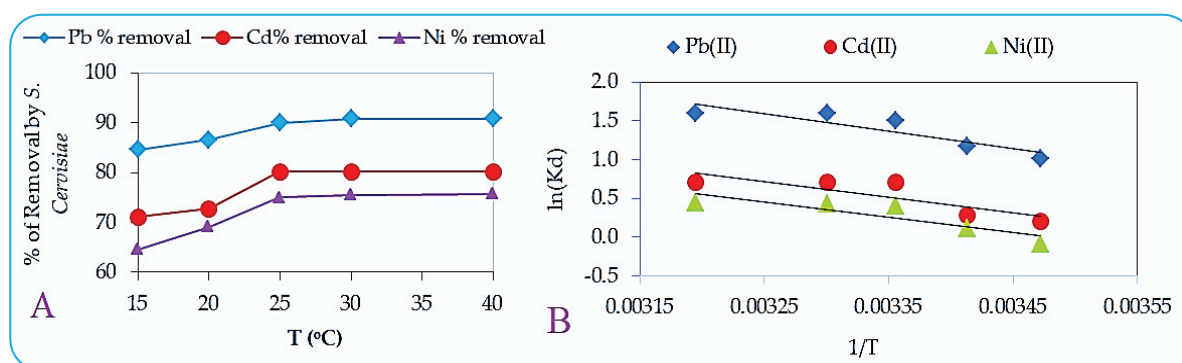


Figure 5. (A) Removal efficiency versus temperature, and (B) $\ln(K_d)$ versus $1/T$ of Cd(II), Pb(II), and Ni(II) ions' adsorption by *S. cerevisiae* biomass.

3.2. Mechanism of *S. cerevisiae*

3.2.1. XRD of *S. cerevisiae*

Figure 6A,D elucidates the chemical nature of yeast cells bound to native lead, cadmium, and nickel, respectively. Figure 6A for native *S. cerevisiae* biomass is expected to be amorphous. Figure 6B depicts lead accumulation in five distinct peaks at 2θ : 21.67° , 27.71° , 31.31° , 41.19° , and 44.08° , corresponding to respective d-spacing 4.15, 3.40, 3.36, and 2.19 Å. Based on spacing values, these peaks are ascribed to the presence of crystalline lead sulfate compounds ($Pb_3O_2SO_4$ and Pb_2OSO_4 , $Pb(SO_4)$ and Pb_2OS_4). Extracellular Pb-containing minerals are lead sulfate [48].

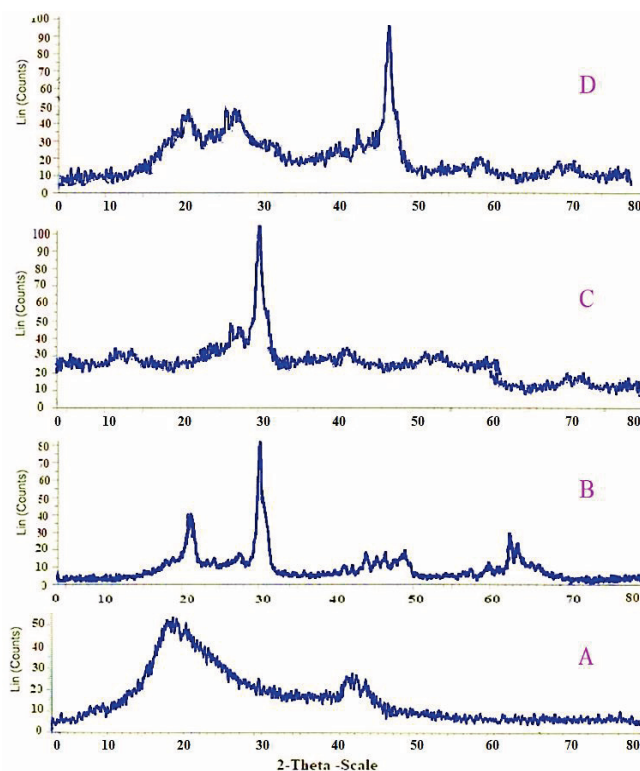


Figure 6. XRD analysis of (A) native, (B) lead-loaded, (C) cadmium-loaded, (D) nickel-loaded *S. cerevisiae* biomass.

Figure 6C presents the XRD pattern of *S. cerevisiae* loaded by cadmium, which shows distinct peaks at 2θ , 43° , and 52.28° , which belong to (110) and (111) planes of the $Cd(OH)_2$ crystalline structure with a hexagonal phase, which concurs with JCPDS card No. 31-0228, while the distinct peak at 30.33° belongs to the $Cd(OH)_2$ monoclinic phase, which is ori-

ented along (110) reflection planes as per JCPDS card No. 84-1767. The low reflection at 2θ 27.4° , corresponding to the plane (210), is attributed to the presence of cadmium chloride phosphate (JCPDS cards 29-0254 and 30-0206). Extracellular Cd-containing minerals (cadmium hydroxide and cadmium chloride phosphate) were observed on the cell wall.

In Figure 6D, the mean peak at 47.8° is indexed to the (132) and corresponds to $1.90 \text{ \AA}$, and the other peak at 22.18° is indexed to the (130) corresponding to the respective d-spacing $4.005 \text{ \AA}$, which indicate the presence of nickel orthophosphate octahydrate ($\text{Ni}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) (JCPDS No.19033-89-7) and hexagonal phase Ni_2P (JCPDS No. 74-1385, $P6_2m$, $a = 5.859 \text{ \AA}$, $c = 3.382 \text{ \AA}$), while the diffraction peaks at 43.85° , 42.6° , and 59° are indexed to the (100), (111), and (102), which belong to Ni_2O_3 (JCPDS 14-0481), NiO_2 (JCPDS 89-8397), and Ni (JCPDS 89-7129), respectively. The extracellular Ni-containing minerals are nickel phosphide, nickel orthophosphate octahydrate, nickel oxide, and nickel dioxide.

3.2.2. FTIR of *S. cerevisiae* and Its Impact on Biosorption of Investigated Metal Ions

To investigate the impacts of Cd(II), Pb(II), and Ni(II) on the properties of cell walls, the *S. cerevisiae* functional groups were investigated with and without the examined metal ions using FTIR analysis. The infrared spectra FTIR of native *S. cerevisiae* and metal-loaded ones were recorded over the range of $300\text{--}4000 \text{ cm}^{-1}$. Native *S. cerevisiae* biomass displays a different FTIR spectrum in Figure 7A; the mean peak at 3413 cm^{-1} is characteristic of hydroxyl O-H and N-H stretching vibrations, while the peak at 2928 cm^{-1} refers to the methyl groups' (C-H) asymmetric stretching [48]. Furthermore, the band at 1644 cm^{-1} proved the vibration C=O of the acetyl group and the deformation N-H of the amide (II) group at 1550 cm^{-1} refers to the stretching (C-N, and N-H) of amides II from proteins, and 1380 cm^{-1} belonged to the carboxyl group appearance (COO^-) in proteins. In addition, the band that appeared at 1239 cm^{-1} refers to a strong symmetrical stretching vibration of the phosphodiester group [$\text{vs}(-\text{PO}_2^{2-})$] in DNA and RNA and phospholipids groups, and 1072 cm^{-1} appertains to the $\beta(1\rightarrow3)$ stretching of glucan and S=O. Finally, the peak at 537 cm^{-1} was assigned to an asymmetrical stretching vibration of PO_4^{3-} , which reveals that the phospholipid bi-layers also exist in yeast cells. From the abovementioned, the primary functional groups of the native fungal cells of *S. cerevisiae* are the hydroxyl, amide, acetyl, methyl/methylene, carboxyl, phosphoryl, and nitro groups. All of these functional groups or active binding sites can be utilized to assess the efficacy of the biosorption process since they are engaged in the retention of metal ions from the solution [48].

On the other hand, the changes in the vibrational frequencies identified through FTIR clarified the engagement of the *S. cerevisiae* cell wall in Pb(II) removal (Figure 7B). The biosorption of Pb(II) on the *S. cerevisiae* surface led to a shift in wavelength by -10 to -1 cm^{-1} . When compared to the original sample, the peak 1239 cm^{-1} had not changed, indicating that the lead atoms did not bind to the phosphate group. However, some peaks had a slight shift to a lower wavelength ($3413\text{--}3407$, $2928\text{--}2926$, $1644\text{--}1641$, $1550\text{--}1543$, $1380\text{--}1373$, $1072\text{--}1062$, and $537\text{--}535 \text{ cm}^{-1}$), suggesting the intervention of hydroxyl, methyl, acetyl, carboxyl, sulfide, Pb-O, and ring deformation groups during Pb(II) adsorption [48,65].

Furthermore, the FTIR spectral analysis of *S. cerevisiae* biomass cadmium-loaded in Figure 7C displays a shift in the wavelength from -19 to $+11 \text{ cm}^{-1}$. When compared to the native cells, the peaks displayed at 1072 and 1550 cm^{-1} disappeared completely after Cd(II) ions, which means that amides II and S=O participated in the biosorption of cadmium ions. Some peaks had a slight shift to a lower wavelength ($1380\text{--}1378$, $1644\text{--}1625$, and $537\text{--}520 \text{ cm}^{-1}$), whereas others had a significant shift to a higher wavelength in peaks ($3413\text{--}3420$, $2928\text{--}2930$, and $1239\text{--}1250 \text{ cm}^{-1}$) after Cd(II) treatment. The shift to low and higher wavelengths could imply that the carboxyl, acetyl, methyl, hydroxyl, and phosphate groups were engaged with the binding of Cd(II) on the cell wall [66].

The FTIR spectral analysis of *S. cerevisiae* biomass nickel-loaded in Figure 7D displays a shift in wavelength by -23 to $+2 \text{ cm}^{-1}$. The peaks displayed at 2350 and 535 cm^{-1} vanished completely when compared to the native sample, implying that the phosphate group participated in nickel biosorption. The peak 1072 cm^{-1} demonstrated no difference

with respect to original yeast because nickel atoms did not bind to the sulfide and glucan groups. Furthermore, significant shifts to a low wavelength in peaks 3413 – 3395 cm^{-1} , 2928 – 2924 , 1644 – 1621 , 1550 – 1541 cm^{-1} , and 1380 – 1373 cm^{-1} after Ni(II) treatment might imply the involvement of the methyl, hydroxyl, acetyl, amide, and carboxyl groups, while a shift to a higher wavelength in peak 1239 to 1241 cm^{-1} suggests the phosphate group was involved in the binding of Ni(II) on the cell wall [67].

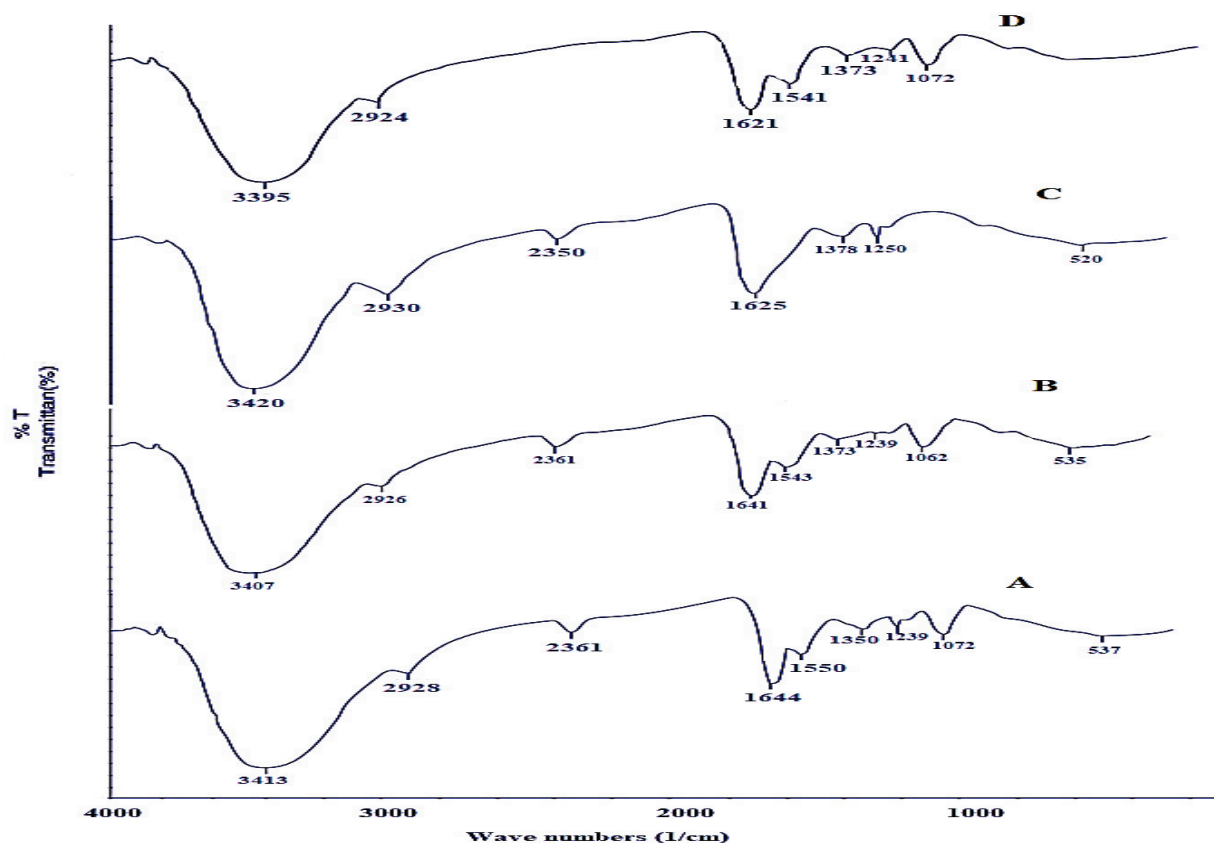


Figure 7. FTIR spectrum of raw *S. cerevisiae* (A) and lead- (B), cadmium- (C), and nickel (D)-loaded *S. cerevisiae*.

Finally, there was a shift to low and high wavelengths in the peak bands of treated *S. cerevisiae* stacked with the investigated metal ions. These deformations of peaks presented in the FTIR spectrum can be surveyed as evidence of biosorption. In addition, no new absorption bands were found to be pertinent for showing that the biosorption of investigated metal ions is not involved in the formation of covalent bonds and that it is performed predominantly through ion-exchange interactions (that are electrostatic) [48,65–67].

3.2.3. Surface Area of *S. cerevisiae*

The previously mentioned features of yeast by FTIR with its large surface area ($252.6 \text{ m}^2/\text{g}$) make it capable of holding heavy metals through biosorption, see Table 6. The nitrogen adsorption–desorption isotherms of the raw *S. cerevisiae* and Pb-loaded *S. cerevisiae* are identified as type IV following the IUPAC “International Union of Pure and Applied Chemistry” classification (Figure 8A,B). This kind of isotherm is characteristic of mesoporous adsorbents for the *S. cerevisiae* and Pb-loaded *S. cerevisiae* and is preferred for the process of ion exchange as it provides more access sites for sorbate cations to reach the internal porosity. The surface area of yeast was reduced from $252.6 \text{ m}^2/\text{g}$ to $225 \text{ m}^2/\text{g}$ after the biosorption of Pb(II) (Table 6). The depletion in surface area can be credited to the creation of new surfaces in inactivated *S. cerevisiae* by physical entrapment and ion exchange.

The prepared yeast has a higher surface area than is found in the literature [24,54], which confirms the higher result of $q_{\max}$ than is found in the literature.

Table 6. Brunauer–Emmett–Teller (BET) analysis for raw and Pb(II)-*S. cerevisiae* biomass.

	Surface Area	Average Particle Size	Total Pore Volume
<i>S. cerevisiae</i>	252.6 m ² /g	4.60667 nm	0.581792 cc/g (cm ³ /g)
Pb(II)-loaded <i>S. cerevisiae</i>	221.97 m ² /g	4.60667 nm	0.511272 cc/g (cm ³ /g)

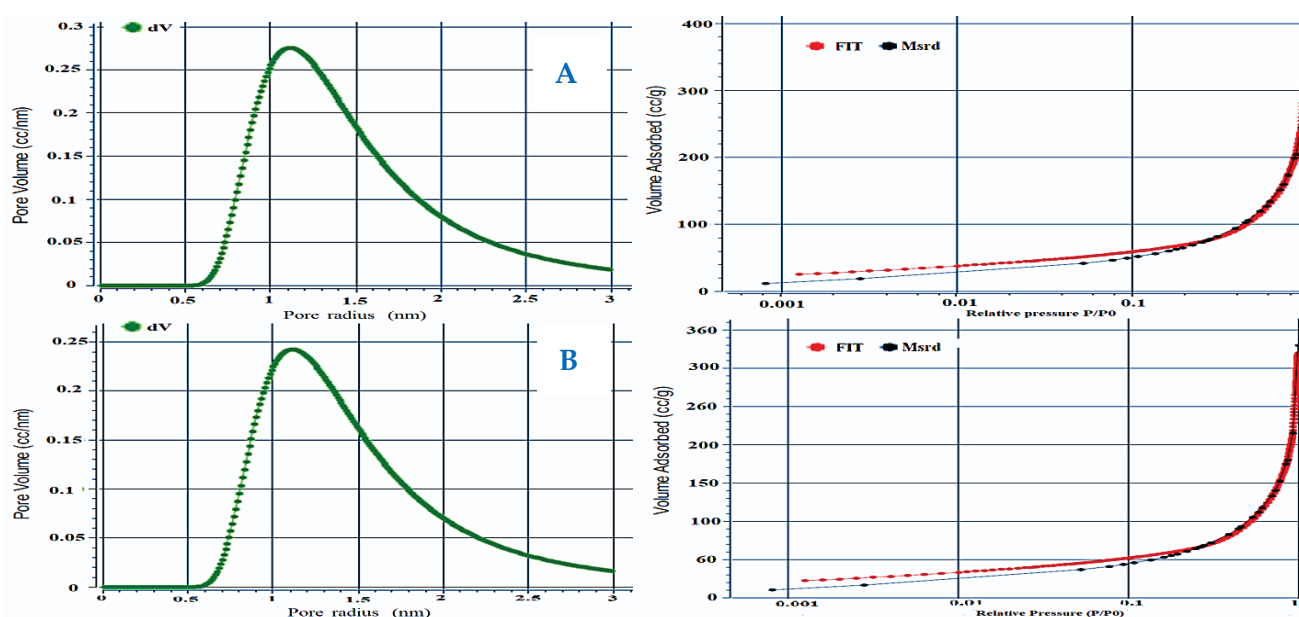


Figure 8. N₂ sorption isotherms for the hydrothermal alkali-activation products of *S. cerevisiae* (A) and Pb-loaded *S. cerevisiae* biomass (B).

3.2.4. TEM of *S. cerevisiae*

Transmission electron microscopy (TEM) was utilized to pinpoint mineral phases inside and on cell walls as well as their morphology. TEM was performed to observe the extent of morphology differences before and after the biosorption of metal by *S. cerevisiae* (Figure 9A,B). It was evident that the *S. cerevisiae* morphology can facilitate the sorption of Pb²⁺ because of its cellular surface being smooth with no membrane dentitions and the uniform electron-dense area across the monocyte body of the stain. After the biosorption of Pb(II), it was deposited inside and outside the *S. cerevisiae* and formed an irregular surface of the biosorbent materials that had fractions of mesoporous particles (Figure 9B). Various examinations have affirmed that numerous fungi can accumulate significant trace elements in their cells, without annihilating the integrity of the cells [68–70]. Intracellular Pb(II) transport occurs through binding to intracellular metal or sequestering sites that have a stronger affinity than cell surface binding sites, and this provides a driving force for intracellular biosorption [68–70]. Accordingly, the fungi developed a mechanism to remove toxins within the cell. Hence, the efficiency of *S. cerevisiae* required a sufficient morphology for the biosorption of mineral particles formed within cells to create a crystalline structure.

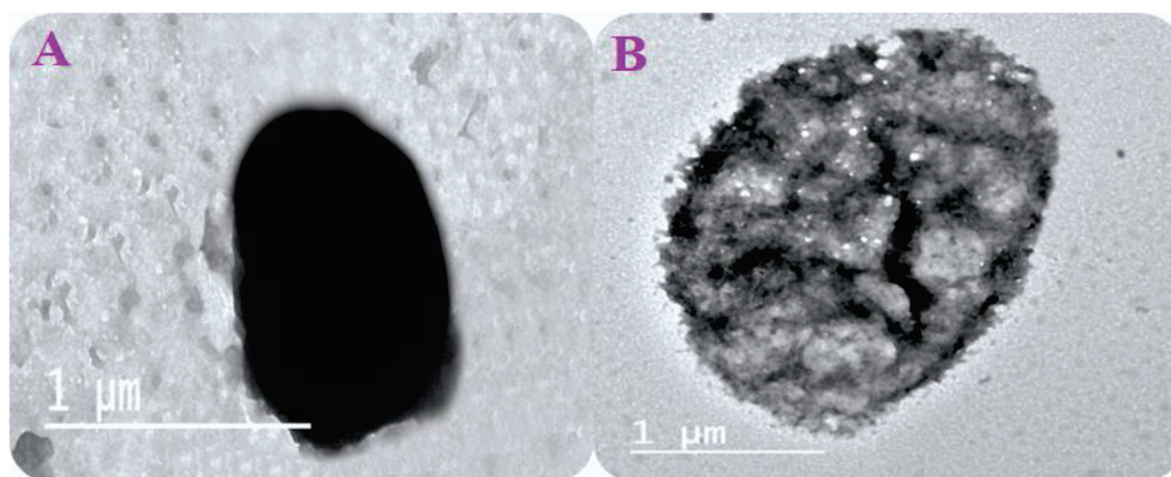


Figure 9. TEM images where (A) TEM native *S. cerevisiae* and (B) loading with lead.

3.3. Biomass Regeneration (Desorption)

Metal desorption from the immobilized yeast cells can result in biomass regeneration as well as valuable metal reclamation. Desorption is necessary when the preparation and production of biosorbent is expensive.

In the present investigation, various types of desorbents solutions (H_2O , NH_4NO_3 , EDTA, and citric acid) were used in three cycles to desorb Cd(II), Pb(II), and Ni(II) ions from immobilized *S. cerevisiae*, see Figure 10. The obtained data show the degree of desorption of Cd(II), Pb(II), and Ni(II) from immobilized *S. cerevisiae*. EDTA and citric acid characterize the highest desorption (80 ± 4 , $90 \pm 5\%$, respectively) because of their ability to form a wide variety of complexes as chelating agents. The EDTA can desorb not only the metal associated with physical entrapment, exchanged but also metal complexes with functional groups, while citric acid has the ability to desorb metal associated with physical entrapment, exchanged, complexes, and parts from the residual metals, which are bio-accumulated. It is suggested that H_2O (12–20%) and NH_4NO_3 (38–45%) display the lowest and medium, respectively, desorption capacities to Pb(II), Cd(II), and Ni(II) ions from *S. cerevisiae*. The lowest desorption by H_2O can be credited to the physical entrapment in which the metal ions are easily susceptible to desorption by water because they weakly bind metals to the cell surface, while the medium desorption using NH_4NO_3 can be ascribed to the ion exchange with Na^+ , Ca^{2+} , K^+ , and Mg^{2+} on the cell *S. cerevisiae* wall.

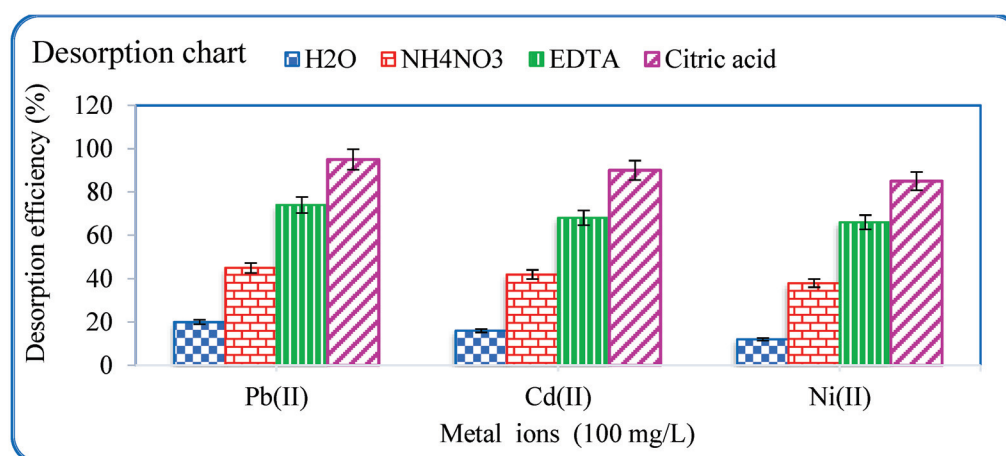


Figure 10. Desorption efficiency (%) of metal ions (100 mg/L for each) biosorbed by immobilized *S. cerevisiae* yeast cells by H_2O , NH_4NO_3 , EDTA, and citric acid. Error bars represent standard deviation.

3.4. Corn Industrial Effluent Treatment

The outcomes of the physicochemical analyses of wastewater samples from the corn factory are displayed in Table 7. The normality test was applied to the researched variables and exhibited that the test showed significant values ($p > 0.05$) for all variables, which affirmed that the examined water quality variables have a normal distribution. The comparison of the two approaches: raw *S. cerevisiae* AP1 and immobilized *S. cerevisiae* AP2 (fixed-bed column) for the treatment of effluent wastewater are displayed in Table 7. Statistically, the analytical data indicated that both the *S. cerevisiae* and fixed-bed column utilized for wastewater remediation demonstrated significant differences (<0.05) for all examined water quality variables. The pH of the solution was slightly alkaline, ranging between 7.6 and 8.2. *S. cerevisiae* showed good activity for the removal of calcium, sodium, potassium, and magnesium ions, with significant variation ($p < 0.05$) from food effluent.

Table 7. Water quality parameters of raw wastewater, and treated water after the application of *S. cerevisiae*, p -value, and their removal efficiency (RE%). (n = 3 samples).

Parameters *	Raw Wastewater				Treated Water with <i>S. cerevisiae</i> (AP1)				Treated Water with <i>S. cerevisiae</i> Uploaded on Calcium Alginate (AP2)					
	Min	Max	Average	p	Min	Max	Average	p	RE (%)	Min	Max	Average	p	RE (%)
pH	6.7	6.9	6.8 ± 0.11 ^B	Less than 0.05	7.5	7.7	7.6 ± 0.10 ^A	Less than 0.05	−11.8	8.1	8.2	8.2 ± 0.01 ^A	Less than 0.05	−11.6
Ca ²⁺	400.5	483.8	453.3 ± 45 ^A		11.6	13.9	13.1 ± 1.27 ^B		97.1	12.6	25.5	20.5 ± 6.9 ^B		95.5
Mg ²⁺	1148.6	1332.8	1255.0 ± 49 ^A		112.5	131.3	120.5 ± 9.73 ^B		90.4	118.9	152.3	139.3 ± 17.9 ^B		88.9
Na ⁺	1740.0	1918.5	1803.6 ± 99 ^A		54.3	59.6	56.1 ± 3.06 ^B		96.9	54.3	105.8	85.8 ± 27.6 ^B		95.2
K ⁺	763.9	1527.8	1085.5 ± 395 ^A		17.5	35.1	25.0 ± 9.11 ^B		97.7	22.0	50.9	39.7 ± 15.5 ^B		96.3
BOD	8800.0	9220.0	9006 ± 210 ^A		179.9	360.3	240.1 ± 104 ^B		98.0	105.3	244.9	190.7 ± 355 ^B		93.8
COD	11,200	12,100	11,766 ± 493 ^A		400.0	435.8	423.9 ± 20 ^B		96.6	171.3	772.0	558.0 ± 324 ^B		93.5
Cd ²⁺	13.50	16.70	15 ± 1.5 ^A		0.151	0.184	0.167 ± 0.02 ^B		98.9	0.152	0.591	0.420 ± 0.24 ^B		97.2
Pb ²⁺	2.87	3.33	3.04 ± 0.2 ^A		0.029	0.035	0.031 ± 0.002 ^B		99.0	0.2	0.6	0.4 ± 0.05 ^B		97.3
Ni ²⁺	12.00	24.00	18.3 ± 6 ^A		0.253	0.509	0.387 ± 0.1 ^B		97.9	<DL	0.1	0.1 ± 0.280 ^B		96.2

*: The units of variables in Table 7 are mg/L, pH is unitless dimension. Negative values are an indication of the increased pH after the application of treatment. Data represented as mean ± SD of 3 samples. The single alphabetical letters (^A and ^B) in the same column for each studied parameter are significantly different ($p < 0.05$).

On the other hand, it was proved that the competitive outcomes of the biosorption of metals by *S. cerevisiae* followed the order: Pb(II) > Cd(II) > Ni(II). Because lead has a smaller ionic cation radius (4.01 for lead [18]), it has a higher probability of being biosorbed by *S. cerevisiae* than the other metal ions. For a single metal at 25 mg/L, simulated solutions of the efficacy of the removal of Ni(II) and Cd(II) were viewed at 60 and 80%, respectively, and almost 99% for Pb(II), as discussed previously in that investigation, while in food effluent, the efficacy of elimination by *S. cerevisiae* was almost 100% for Pb(II), Cd(II), and Ni(II). The enhanced RE% is attributable to the concentration of a single metal ion solution being 25 mg/L and the concentration of metal ions in real industrial effluent being extremely lower; therefore, a better RE% was taken. Biodegradation of organic compounds by *S. cerevisiae* can be seen as a better activity for the decrease in COD and BOD in the water samples, because *S. cerevisiae* has been portrayed as a strong bio-degrader, particularly for wastes rich in protein and carbohydrates [71,72].

Thusly, *S. cerevisiae* shows a superior reduction in cation, COD, BOD, Cd(II), Pb(II), Ni(II), and Zn(II).

3.5. Storage of the Immobilized *S. cerevisiae*

One of the prime aims of biosorption is to expand the time of storage of *S. cerevisiae*. Consequently, storage stability and reusability of the raw and immobilized system are vital for fruitful bio-treatment and for industrial remediation. As displayed in Figure 11, the immobilized *S. cerevisiae* was very steady when kept at 4 °C for 8 m (months) and showed the strength of the immobilized *S. cerevisiae* in repeated use for eight cycles, with retained RE% up to 90% for the investigated metal ions. Despite this, the raw *S. cerevisiae* was active for 2 m; after that, the RE% decreased by about 44–60%, 52–63%, and 35–48% for Pb(II), Cd(II), and Ni(II), respectively, after storage for 3–8 months. This reinforced that

the stability of immobilized *S. cerevisiae* can be attributed to the autolysis prevention by immobilization, so the immobilized yeast had a greater reduction in metal ion pollutants.

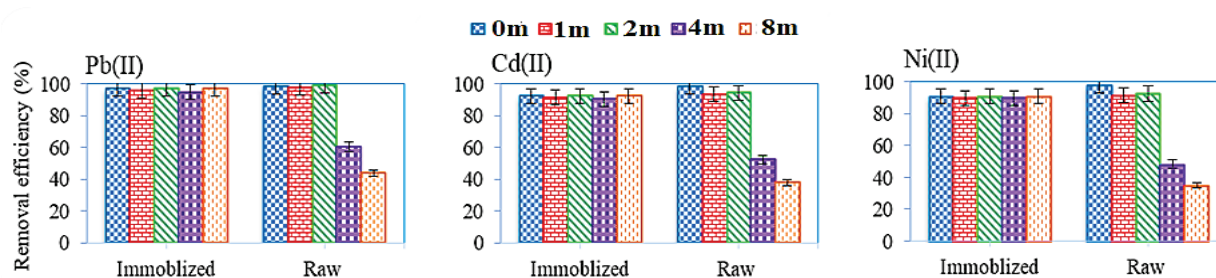


Figure 11. Removal efficiency (%) of Cd(II), Pb(II), and Ni(II) ions by different storage times for immobilized and raw *S. cerevisiae* yeast.

4. Conclusions

The current article showed that *S. cerevisiae* was successfully grown on YPD and had the ability to reduce metal ions from water and effluent. This aspect was confirmed by XRD, TEM, BET, and FTIR outcomes. The yeast has an area of 252.6 m²/g with a mesoporous pore volume, which is higher than what is found in the literature, so the maximum biosorption capacity is 65 for Cd(II), 51 Ni(II), and 90 for Pb(II) mg/g, indicating that the grown and dried method for the yeast enhanced its character. The optimal pH for the removal of Cd(II), Pb(II), and Ni(II) from an aqueous solution is 5 at a contact time of 25 min, 2 g *S. cerevisiae*/L at 25 °C, which allowed the removal of 80, 99, and 70% (25 mg/L), and 72, 90, and 69% (100 mg/L), respectively. The Langmuir isotherm model and the second-order kinetic model were the best models for describing the spontaneous biosorption reactions of the investigated metal ions. A comparison was made between *S. cerevisiae* and a fixed-based column (packed with immobilized *S. cerevisiae*) on a real effluent. The outcomes indicated that both approaches not only remove the examined metal ions, but also cations, BOD, and COD with higher efficiency. EDTA and citric acid have proved excellent outcomes for yeast regeneration. The removal efficiency of the raw *S. cerevisiae* decreased after being kept for 3–8 months. Storage and reusability investigations confirmed the highest operational stability of immobilized *S. cerevisiae* for eight cycles with retained activity up to 90%.

The findings of this examination indicate that the column technique using the immobilized *S. cerevisiae* leads to obtaining the biosorbent that is easy to handle, excellent, stable for months, sustainable, eco-friendly, and can be applied in food industrial effluent treatment.

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Article

Long-Term Assessment of a Water Safety Plan (WSP) in Salta, Argentina

María Soledad Rodríguez-Alvarez ^{1,*}, Aimé Gutiérrez-López ^{1,2}, Martín Alejandro Iribarnegaray ¹, Mark Howard Weir ^{3,4} and Lucas Seghezzo ^{1,2}

¹ Instituto de Investigaciones en Energía No Convencional (INENCO), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de Salta (UNSa), Salta A4408FVY, Argentina

² Facultad de Ciencias Naturales, Universidad Nacional de Salta, Salta A4408FVY, Argentina

³ Division of Environmental Health Sciences, College of Public Health, The Ohio State University, Columbus, OH 43210, USA

⁴ Sustainability Institute, The Ohio State University, Columbus, OH 43210, USA

* Correspondence: soledad.rodriguez@conicet.gov.ar

Abstract: The use of water safety plans (WSPs) has been recommended by the World Health Organization (WHO) since 2004 as a highly effective means of improving water safety management. Experience with the implementation of WSPs is increasing worldwide, but there is no unified or standardized methodology for how the verification of a WSP should be conducted. In this article, we present a thorough evaluation of a specific WSP five years after its initial implementation. We reviewed the risk assessment methodology used by a water utility in Salta, Argentina, and assessed the implementation of control measures. To objectively evaluate the effectiveness of the WSP, we evaluated water quality parameters and customer complaints using a time-series analysis. We show that although some control measures were implemented, and a reduction in risk values was observed, it was not possible to improve long-standing problems in the water supply of the city of Salta, such as the number of consumer complaints or high turbidity levels in the water during the rainy season. We discuss the role of rigorous scientific assessments and the importance of legislation and regulatory bodies in implementing the WSP.

Keywords: effectiveness of WSPs; long-term assessment; risk assessment; water safety plan (WSP)

1. Introduction

In the city of Salta, the water utility has historically experienced two recurring problems: (a) increases in turbidity during the rainy season and (b) associated water outages used as a control measure [1]. To address these and several other relevant water quantity and quality issues, the water utility and local researchers, including some of the authors of this article, set out in 2012 to develop a comprehensive water safety plan (WSP) for the city of Salta [2].

A WSP is a management approach recommended by the World Health Organization and the International Water Association (IWA) since 2004 [3,4]. It is considered the most effective preventive risk management tool for improving water safety [5]. The method is well-described in [6] and elsewhere, especially for small community water supplies [7,8]. The implementation of WSPs is growing steadily across the world. They are increasingly being implemented in water utilities and have also been integrated into policy or regulatory instruments [9].

WSPs have been implemented in both rural and urban areas, and a number of advantages, disadvantages, and challenges have been identified [10–16]. These include the need to set performance targets, identify and monitor evaluation indicators [17], build stakeholder capacity [18,19], educate and train operators [18,20], improve data collection

and recording procedures [21,22], and explore how local legislation [11,23,24] and other factors influence WSP implementation [25].

Rigorous and periodic assessment is critical for proper implementation of any WSP [6]. Studies on the long-term impact of WSPs on drinking-water quality or public health are still limited and mostly focused on high-income countries such as Iceland, Italy, Spain, and France. Quantifying the relationship between drinking water parameters (e.g., turbidity) and gastroenteritis [26,27] or recording the number of quality-related complaints and resolution times [28] can show how a WSP can affect public health.

Argentina has some experience in implementing WSPs [29,30]. In Salta, a professional team developed a WSP that identified a set of control measures needed to minimize risks to water quantity, water quality, and human health [2]. In this paper, we provide a long-term assessment of the implementation of that WSP. Our study was conducted after the control measures had been implemented by the company. We wanted to know whether the WSP had helped to improve some of the long-standing problems of the city's water supply. We provide a brief overview of the risk-assessment process conducted by the company and attempt to determine the impact of the WSP on drinking water quality and public perception. We provide some recommendations to optimize the WSP implementation process. This work provides some tools to improve the long-term assessment of WSPs and may be useful to allow comparisons between WSPs implemented in different cities.

2. Materials and Methods

This study is based on a WSP developed in 2012 for the city of Salta in northwestern Argentina (24°51' S 65°29' W; 1187 m above sea level). The climate is defined as subtropical with a dry season with rain mainly between November and March. The average air temperature is 16.5 °C and the annual rainfall is about 700 mm [31].

The water supply of the city of Salta is managed by the state-owned company Aguas del Norte (AdN). Water supply can be divided into four basic processes: catchment, transport, potabilization, and distribution. Water is obtained from surface, subsurface, and subterranean sources. Surface and subsurface water is transported from the catchment area through open and closed aqueducts to treatment plants, where it undergoes sedimentation, filtration, and chlorination processes depending on the characteristics of the water. Groundwater is obtained from more than 169 deep wells distributed throughout the city and is treated only with chlorine. After drinking-water treatment, the water is distributed through a distribution system. In some cases, distribution also includes water reservoirs and cisterns.

For the purposes of this study, the systems are classified as System No. 1 (Finca Las Costas), System No. 2 (North System), System No. 3 (South System), and System No. 4 (Wells). System No. 5 is the distribution system common to all the previous systems. The simplified flow diagram of the water system in Salta is shown in Figure 1.

The risk assessment was based on the WSP manual [6] with modifications suggested by Seghezzi et al. [2]. During participatory workshops with a professional team assembled by AdN, the hazardous events for each system were evaluated, assigning probability and severity values on a scale from 0 to 100, which was considered more intuitive and facilitated the evaluation. The probability and severity were estimated based on objective, statistical, or scientific data, such as the probability of earthquakes or droughts or the severity of microbiological contamination of water sources. When quantitative criteria could not be applied, values were assigned based on participants' experiences and opinions. Severity was determined based on the impact of hazardous events on water quantity, water quality, and human health. Risk was calculated as the product of the probability of occurrence of a hazard and the severity of that occurrence, and was ranked according to the following scale: risk < 25: low; $25 \leq \text{risk} < 50$: medium; $50 \leq \text{risk} < 75$: high; risk ≥ 75 : very high (adapted from [32]). An acceptable risk value was set at 24%, one unit below the upper end of the "low" range [2].

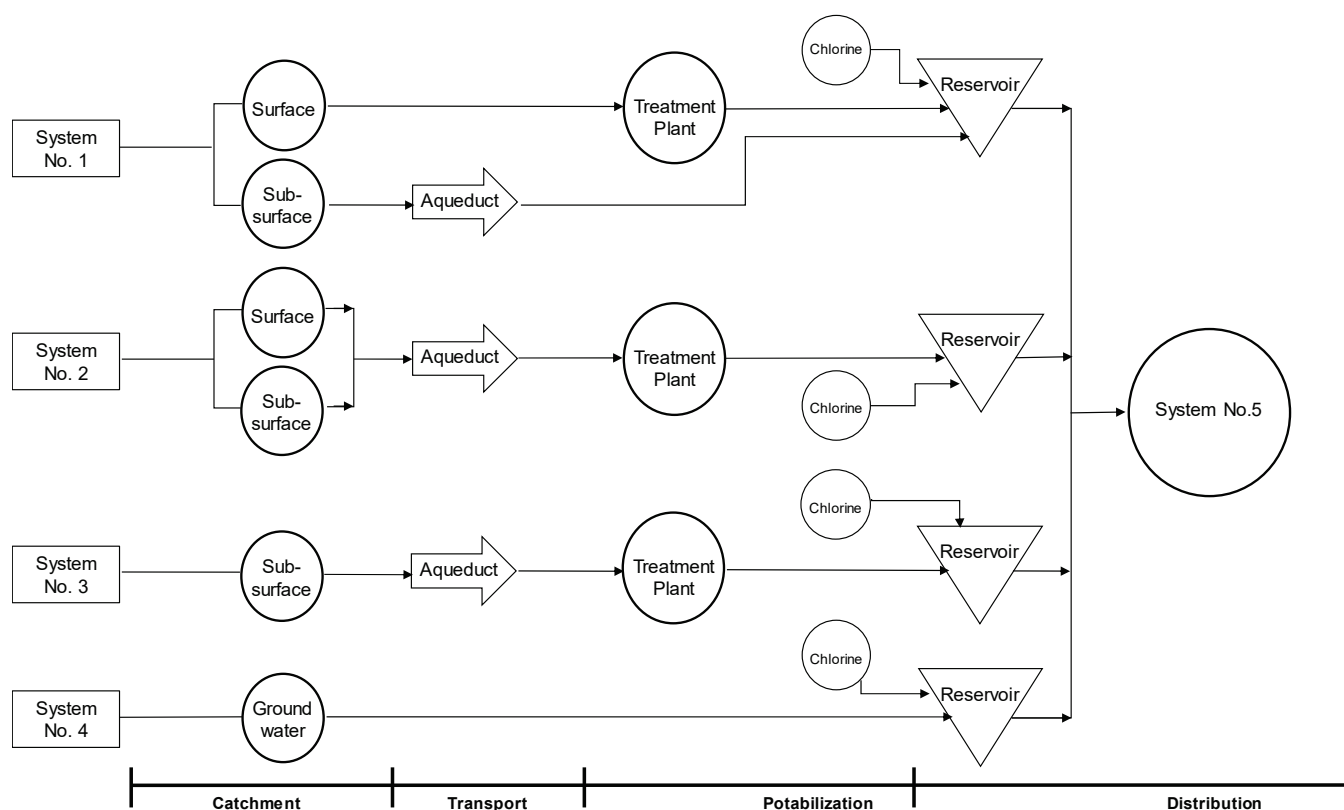


Figure 1. Flow diagram of the water system of the city of Salta. The processes are indicated below the bottom line.

2.1. Review of the WSP

At the beginning of the WSP in 2012, 98 hazardous events were identified, and an initial risk was determined for each system. The water utility has conducted its own annual risk assessment for 5 years since the implementation of the WSP. In this study, we provide a descriptive review of all the activities the company has conducted during this 5-year period. This includes a review of the control measures established for each hazard, an analysis of compliance or noncompliance with the control measures, an analysis of the methodology used to calculate annual risk, and a discussion of how the decrease in annual risk values might be associated with the implementation of the control measures.

2.2. Assessment of the WSP

The company monitors water quality and sends a monthly report to a control body, the Public Services Regulatory Entity (ENRESP, Spanish acronym). Using these reports (from 2011 to 2017), the research team identified indicators that could reflect improvements in the water service in each system under study. These indicators were also discussed in two workshops with members of ENRESP. Two groups of potential indicators were identified: (1) **Complaints**. This group includes all consumer complaints received by the water utility, such as water quality deficiencies (high turbidity, lack or excess of chlorine, among others), lack of water, water delivery requests, tank or cistern overflows, lack of signals at certain locations, poor maintenance of water facilities, water losses, and insufficient water pressure; and (2) **Water quality**. In this group, we included water quality parameters and variables such as turbidity, residual chlorine, and *Escherichia coli* (*E. coli*), considering that legislation allows a maximum of 3 NTU for turbidity, a minimum of 0.2 mg/L for residual chlorine, and the absence of *E. coli* in 100 mL [33].

The systematization of the data was carried out taking into account the totality of neighborhoods distributed throughout the city, which in 2017 were 369 neighborhoods. The results of the analysis of water quality and complaints are assigned to the address

and the associated neighborhood of the consumer. In order to evaluate different systems independently, only neighborhoods that receive water from one system were selected. (In some areas, water from two or more systems is blended prior to distribution.) This limited the available data to Systems No. 1 and No. 2, as most of the available from Systems No. 3 and No. 4 correspond to households receiving mixed water. The results from “Salta City” include all systems (No. 1 through No. 5) as a whole.

To verify the effectiveness of the WSP, the Mann–Kendall test (MKT) and the Pettit test (PT) were applied to water quality variables using XLSTAT software. Both are time-series tests, with the MKT assessing the monotonicity of positive or negative trends and the PT assessing the quantified shifts in the central tendency of the distributions of the data. One of the MKT parameters is Kendall’s tau, whose sign, positive or negative, indicates whether the trend is positive or negative when the p -value is less than the significance level alpha (in our case, alpha = 0.05). The PT is an adaptation of the MKT that identifies the moment when a significant change occurs in the mean of the evaluated values and the date when the change occurs. The analysis shows the date of the change in the mean and the value of the corresponding means μ_1 and μ_2 . These tests have also been used in the evaluation of hydrologic time series collected over several years [34–36]. A summary of the data analysis described can be found in Table 1.

Table 1. Variables and data analysis methods used in this study.

Parameters	Data Used	Period	Systems	Method
Complaints	Number of complaints	2011–2017	Salta city/System No. 1/System No. 2	MKT-PT
Turbidity	All available data	2011–2017	Salta city/System No. 1/System No. 2	MKT-PT
Turbidity	Number of deviations (turbidities greater than 3 NTU) per month per year	2011–2017	Salta city/System No. 1/System No. 2	MKT-PT
Chlorine	Amount of deviations (chlorine values less than 0.2 mg/L) per month per year	2011–2017	Salta city	MKT-PT
<i>E. coli</i>	All available data	2011–2017	Salta city	MKT-PT

3. Results and Discussion

3.1. Review of the WSP

3.1.1. Review of Control Measures

The complexity of the water supply of the city of Salta required a painstaking effort by the company to establish the control measures for each hazardous event.

One or more control measures were assigned to each hazardous event. For example, in one case where unexpected flooding occurred and posed a hazard to the water-treatment process, three control measures were implemented: (1) a shutdown procedure for the potabilization plant; (2) an alternative water source; and (3) new infrastructure such as physical barriers in the river to protect areas from flooding. Table 2 shows a summary of the systems, the associated sub-processes (14 in total), the number of hazardous events, and the number of control measures associated with each system. Table S1 in the supplemental material shows the hazardous events and control measures for each process of each system.

Table 2. Summary of systems, sub-processes, number of hazardous events, and number of control measures.

Systems	Sub-Processes	Number of Hazardous Events in Each Sub-Process	Number of Control Measures in Each System
System No. 1	Sub-surface catchment	5	26
	Surface catchment	11	
	Transport	4	
	Potabilization	8	
System No. 2	Sub-surface catchment	9	25
	Surface catchment	7	
	Transport	8	
	Potabilization	7	
System No. 3	Sub-surface catchment	7	11
	Transport	6	
	Potabilization	2	
System No. 4	Groundwater catchment	9	18
	Potabilization	5	
System No. 5	Distribution	10	20
TOTAL	14 sub-processes	98 hazardous events	100 control measures

3.1.2. Analysis of Compliance with Control Measures and Annual Risk Calculation

Annually, the WSP team evaluated compliance with each control measure and recalculated the risk level for each hazardous event based on their own risk-estimation approach. The risk values for Systems No. 1 to No. 5 were determined by averaging all risk values calculated for each corresponding subprocess. Finally, a global risk value for the city of Salta was estimated as the average of all risk values for all systems.

The company risk calculation method included three variables: (1) the initial risk from hazard i ($X_{i,0}$); (2) the compliance for each control measure adopted for hazard i (C_i); and (3) the impact value of that control measure to minimize risk (I_i). I_i is an arbitrary variable defined by the company to weight each control measure. The company considered that different control measures have a different impact on mitigating hazard i . However, the sum of the impacts would still need to be within the range (0,1). Therefore, they use Equation (1), in which the sum of changes from subsequent years since WSP implementation is subtracted from $X_{i,0}$.

$$X_{i,n} = X_{i,0} - \sum_{j=1}^p (X_{i,0} \cdot I_{i,j} \cdot C_{i,j,n}) \quad (1)$$

For a hazard i with p control measures, ($X_{i,n}$) is the risk value in the year n ; $I_{i,j}$ is the impact of the control measure j ; and $C_{i,j,n}$ is the percentage of compliance with the control measure j in the year n . The values for $I_{i,j}$ were established only once at the beginning of the WSP through internal workshops using an expert elicitation process. The values for $C_{i,j,n}$, on the other hand, were discussed annually among the members of the company and reviewed internally.

Table 3 shows this assessment for two example hazards and their corresponding control measures for catchment used for System No. 1.

Following the examples in Table 3, two control measures with the same 50% risk mitigation impact were defined for hazard 1. For hazard 2, fencing in the catchment area to prevent livestock entry is assumed to reduce risk by only 5%, so additional measures must be taken to regulate the presence of livestock in the area. Housing livestock in appropriate areas could have a 20% impact, and building a new water-treatment plant would have a 70% impact. In terms of percent compliance, 0% compliance means the control measure was not implemented, while 100% means it was fully complied with. The percentages

in between (70%, 50%) mean that the control measure is still in progress. Table S1 (last column) in the supplemental material shows compliance with each control measure.

Table 3. Example of risk calculation for two hazards.

Hazards (<i>i</i>)	Control Measures (<i>j</i>)	$I_{i,j}$	$C_{i,j,n}$	$X_{i,0}$	$X_{i,n}$
1. Recreational misuse	1. Fence in the catchment area.	$I_{11} = 50\%$	$C_{111} = 100\%$	$X_{10} = 47\%$	$X_{11} = 7\%$
	2. Work in cooperation with the competent entity to establish access restrictions in the catchment areas.	$I_{12} = 50\%$	$C_{121} = 70\%$		
2. Domestic and livestock animals	1. Agreeing on the regulation of livestock with the manager of the protected area.	$I_{21} = 5\%$	$C_{211} = 50\%$	$X_{20} = 100\%$	$X_{21} = 92\%$
	2. Housing of livestock in suitable areas.	$I_{22} = 20\%$	$C_{221} = 0\%$		
	3. Fencing in of the catchment area.	$I_{23} = 5\%$	$C_{231} = 100\%$		
	4. Construction of a new water-treatment plant.	$I_{24} = 70\%$	$C_{241} = 0\%$		

Based on this risk-calculation method, the annual changes in risk values for all systems studied with their respective sub-processes are shown in Figure 2.

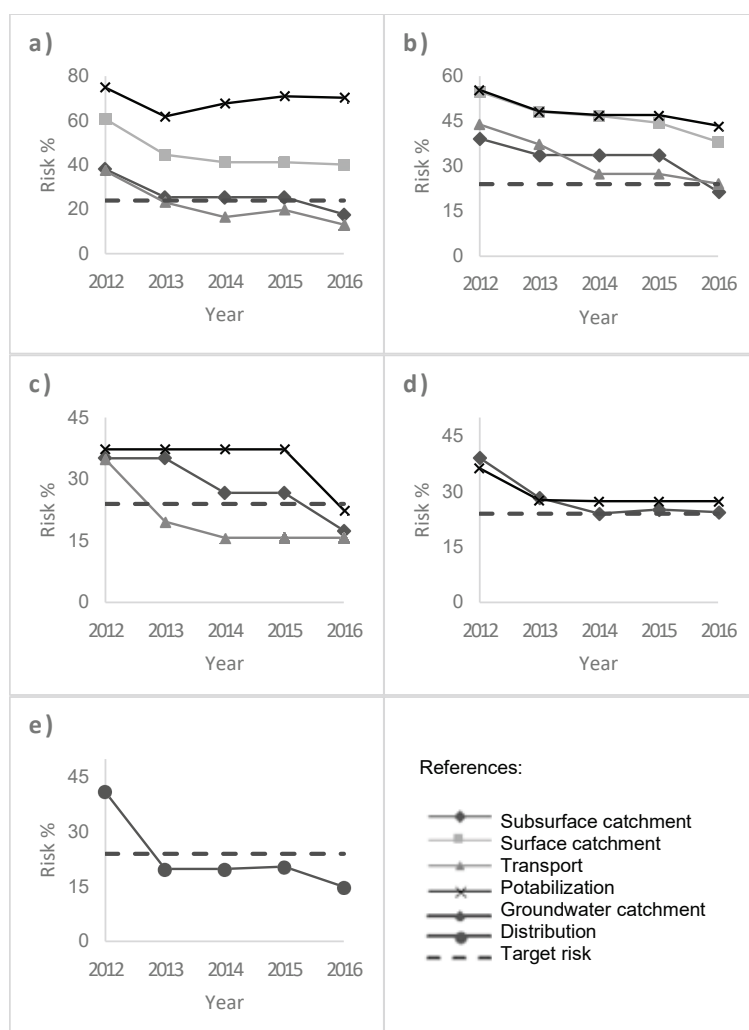


Figure 2. Risks of the individual processes of each system: (a) System No. 1; (b) System No. 2; (c) System No. 3; (d) System No. 4; and (e) System No. 5. Dotted line: target risk (24%).

It can be seen that the risk in all sub-processes exceeded the acceptable risk threshold of 24% by 2012 and gradually decreased with the implementation of various control measures. In 2016, the risk was reduced below the threshold except for the sub-processes of “Surface catchment” and “Potabilization” in Systems No. 1 and No. 2. The sub-process of potabilization of System No. 4 was slightly above the target risk (27%).

The company considers this methodology to be the best alternative for assessing its risks and agrees with the recommendations of Bartram et al. [6], according to which the WSP methodology can be adapted to specific needs. At the internal level of the company, the checklist of control measures has allowed the development of an orderly and thorough work plan to verify compliance and annual progress.

However, the specificity of the method used by the company must be verified, in particular, with regard to possible improvements to Equation (1), especially to the variable used, $I_{i,j}$. This variable was adopted based on expert opinion in a workshop, but the ability to justify that a particular control measure can reduce a risk value by a certain percentage was not determined. In addition, many of the control measures established by the company had not yet been put into practice, so it might be more reasonable to determine the impact value ($I_{i,j}$) after the control measures had been implemented. Using Equation (1) gave them a false sense of security about the effectiveness of the WSP they had implemented.

Those control measures that have not been implemented after 5 years deserve special attention because there is a latent hazard and unresolved risk over 5 years. Compliance with control measures in each system was analyzed, and it was found that 37% of the control measures proposed in 2012 had not been implemented 5 years after the implementation of the WSP. The complexity and cost of the unimplemented control measures varied widely, and it was not possible to identify the order of priorities established by the company. Some of the unimplemented control measures included construction of physical barriers in the river course to prevent flooding, system improvement studies, optimization of the piping system, optimization of the water treatment system, replacement of the filter bed, expansion of the existing water facilities, implementation of guard rotation services, installation of a generator, monitoring and control of wastewater disposal, and construction of a fence, among others. In Systems No. 1 and No. 2, more than half of the measures proposed at the beginning of the WSP were not implemented. Some of these measures involve low costs, such as installing a generator in case of a power outage, permanent guards in vandalism-prone areas, and building a fence; others involve higher costs, such as optimizing water-treatment systems or expanding existing facilities. If a control measure cannot be met for any reason, the hazard should be reassessed and the need for new control measures considered.

A particularly interesting sub-process is the water-potabilization process of System No. 1 and No. 2, where the initial risk estimates in 2012 were 75% and 55%, respectively. In System No. 1, nine of the twelve control measures had 0% compliance, and control measure impacts ranged from 5% to 70%. In System No. 2, seven of ten control measures had 0% compliance. In particular, the control measure “construction of a new water-treatment plant” is considered to have an impact of 70% to minimize the risks related to agriculture, domestic animals and livestock, insufficient treatment capacity, pollution of water sources, and meteorological and climatic phenomena, so it was considered the most important control measure to improve System No. 1. The surface catchment sub-process is also influenced by this control measure. A similar situation about this control measure is observed in system No. 2. To assess the importance of this facility, two situations were simulated in 2016 using Equation 1. First is Scenario 1, in which the facility is built by 2016, resulting in 100% compliance. In Scenario 2, the company decides to focus on all control measures except the construction of a new water-treatment plant. Since System No. 2 also proposes the execution of a new plant to optimize service, the same scenarios were proposed for this case. In the case of System No. 1, the construction of a new plant would reach a risk value of 22%, while focusing on the implementation of the remaining control measures, as proposed in Scenario 2, would allow a risk of 18%. In the case of

System No. 2, values of 19% and 18%, respectively, would be achieved. In other words, similar results were obtained, with a significant difference in decision making, investments used, and time required to achieve the risk objectives. This analysis is important to decide whether the execution of an investment is really necessary or not and whether it justifies the effort and money.

3.2. Assessment of the WSP

3.2.1. Analysis of Complaints

Between 2011 and 2017, the city of Salta received 658,729 complaints, of which 351,221 corresponded to water service. Data on the evolution of the population served over time were not available.

For the time-series analysis, those 351,221 complaints were considered, of which 11,803 came from System No. 1, and 13,691 came from System No. 2. The results are shown in Figure 3a–c: for the entire city of Salta, System No. 1, and System No. 2, respectively. Trends and significant shifts in the means from the Pettit analysis, indicated by μ_1 and μ_2 , are also shown in these figures.

The city of Salta showed a statistically positive trend (Kendall's tau 0.286, p -value 0.050): an increase in the number of complaints, which showed a significant change in September 2014 by the Pettit test. System No. 1 is observed to have a negative trend in the number of complaints (Kendall's tau -0.309 , p -value < 0.0001) and a significant change in March 2015. System No. 2 showed no trend shifts in the data series during the studied period (p -value 0.310), indicating that the number of complaints neither improved nor decreased.

The WSP shows that although the city of Salta's risk has decreased since the implementation of the WSP, this has had no effect on the number of complaints about the quality of water service (Figure 3). Pettitt's analysis shows that there was an increase in the average score in September 2014. At that time, the company indicated that it was able to identify the absence of a filter bed in a potabilization process while monitoring compliance with control measures. The increase in complaints coinciding with that date suggests that this aspect may have an impact on the quality of the service.

Regarding System No. 1, which has a negative trend in the number of complaints and a significant change in March 2015 (Figure 3), there is no specific control measure that influenced a decrease in risk in 2015. However, from 2012 to 2016, some control measures were implemented in all sub-processes that could be associated with the negative trend in the number of complaints, mainly measures that increase the safety of the catchment areas, inspection of the facilities, and permanent staff for the operation of the water-treatment plant. Likewise, action plans have been developed to address meteorological and climatic phenomena such as droughts and floods. These include the use of alternative water sources, the possibility of closing water intakes when turbidity exceeds the treatment capacity of the plant, the development of prevention and emergency plans, and the training of all personnel and the implementation of drills for emergencies. On the other hand, the company worked with external stakeholders to regulate agricultural and livestock activities in the catchment area, the location of livestock in appropriate areas, and prohibiting recreational activities in catchment areas. These actions, which are not significant investments but rather important management improvements, may have had an impact on the observed decline in complaints.

System No. 2 did not show statistically significant changes; i.e., the control measures implemented that led to a decrease in risk did not affect the number of user complaints. Furthermore, the control measures proposed at the beginning of the WSP, which were aimed at minimizing the hazards related to meteorological and climatic phenomena, lack of safety in the sub-processes, erosive phenomena, insufficient treatment capacity, power failure, and pollution sources, were not implemented at any time during the period studied.

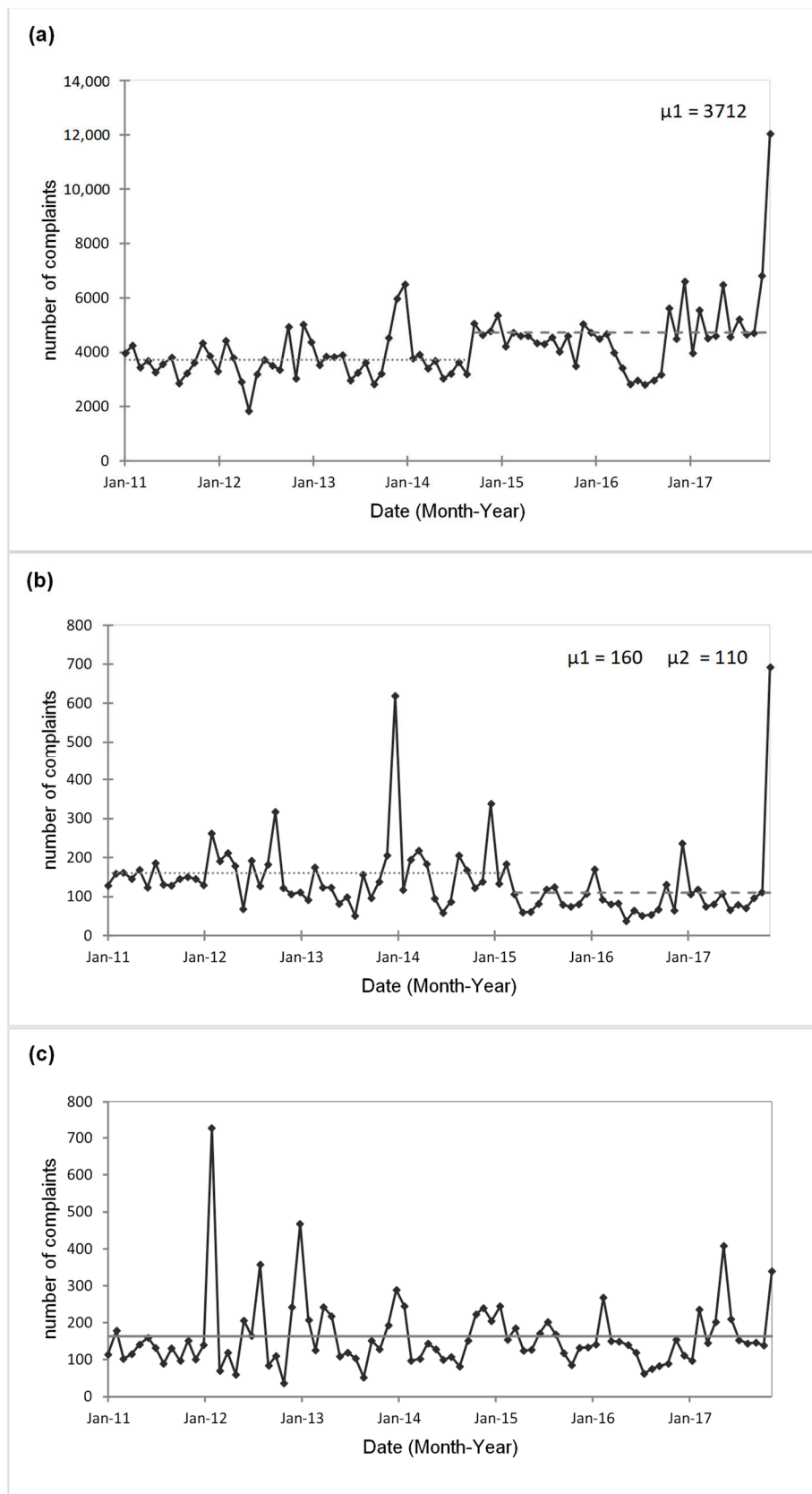


Figure 3. Time-series analysis of complaints. (a) City of Salta; (b) System No. 1; and (c) System No. 2. The date format for the x-axis is month-year. Significant shifts and their values from Pettit analysis are indicated by μ_1 (dotted line) and μ_2 (dashed line).

3.2.2. Time-Series Analysis of Water Quality Parameters

Table 4 shows the amount of data available for each of the systems considered in this phase. For the turbidity indicator, a trend analysis was performed for the three systems considered, while for the residual chlorine and *E. coli* indicators, the data analysis, ordered by the number of deviations per month per year, was performed only for the city of Salta since only a limited number of deviations were observed in Systems No. 1 and No. 2.

Table 4. Available and deviated data (years 2011–2017).

System	Turbidity Data		Residual Chlorine Data		<i>E. coli</i> Data	
	Available	>3 UNT	Available	<0.2 mg/L	Available	Presence of <i>E. coli</i>
Salta city	35,341	2247	35,577	786	34,831	145
System No.1	1297	432	1320	40	1268	11
System No.2	1085	203	1129	4	1060	5

Figure 4 shows the results of a Mann–Kendall analysis for the city of Salta. In both the analysis of all available turbidity values ($p = 0.759$) (Figure 4a) and the analysis of the number of deviations, i.e., turbidities greater than 3 NTU ($p = 0.311$) (Figure 4b), no statistically significant changes were found that would explain a change in the trend of the values. It should be noted that none of the control measures taken were sufficient to prevent turbidity spikes during the summer. Similarly, most records of turbidity values above 3 NTU occur primarily in December, January, and February of each year, as shown by the peaks in both Figure 4a,b. This behavior did not change over time; i.e., the WSP had no relationship with this variable. The values for System No. 1 behaved similarly to those for the entire city of Salta both for all turbidity values ($p = 0.902$) and for the number of values above 3 NTU per month-year ($p = 0.323$).

System No.2 registered a statistically negative trend (Kendall's Tau = -0.118 ; $p = 0.002$), with a significant change in the mean in March 2014 ($p < 0.0001$) (Figure 5a). Control measures that may have contributed to the reduction in turbidity included catchment area access restrictions, closure of water intakes after heavy rains, alternative water sources (such as groundwater), leakage reduction, and more stringent water quality controls. As shown in Figure 5b, there was no trend in turbidity levels greater than 3 NTU. The lack of negative trends and the peaks above 3 NTU during the rainy season indicate that more effective control measures are still needed.

In the three systems studied, “water loss” and “lack of water” accounted for most complaints, with a peak of 78% of complaints in 2016 (46% for water loss and 32% for lack of water). This behavior is related to inadequate infrastructure to address high turbidity levels, as the control measure for turbidity is to turn off the water intake. An important finding was that water quality complaints account for only 2% of all complaints, considering that the time-series analysis of turbidity levels shows significant turbidity spikes during the rainy season that far exceed the maximum allowable value of 3 NTU, including a maximum value of 124 NTU for System No. 1. Furthermore, the turbidity levels do not improve over time. This means that the consumer receives turbid water at home but does not complain to the company. This acceptance of the turbidity problem would also be a good point to evaluate in the near future, as perhaps this is the reason that complaints of high turbidity do not prevail. It is important to consider what actions people take when they receive turbid water in their homes: whether they drink it no matter what, whether they buy water, or whether they use some other method to treat drinking water. There is no evidence of community warnings to take complementary water-treatment measures, such as boiling or additional filtration, when it is clear that turbidity levels greater than 30 NTU, as observed in 2016, are perceptible to any consumer and because high turbidity also complicates the subsequent chlorination process and bacteriological treatment [37]. A study by Kumpel et al. [22] in the Asia-Pacific region found that infrastructure improvements focused on water quality rather than water quantity, while consumer complaints focused primarily

on water quantity. This highlights the importance of balancing both aspects in water safety planning, but it is also important to consider the social perspective when making decisions [38].

Figure 6 shows the data analysis on the amount of chlorine less than 0.2 mg/L in the city of Salta per month-year. A change in the mean is observed in March 2012 ($\mu_1 = 17.3$; $\mu_2 = 7.6$; $p = 0.002$). A MKT with data after that date (2012 to 2017) indicates no statistically significant change.

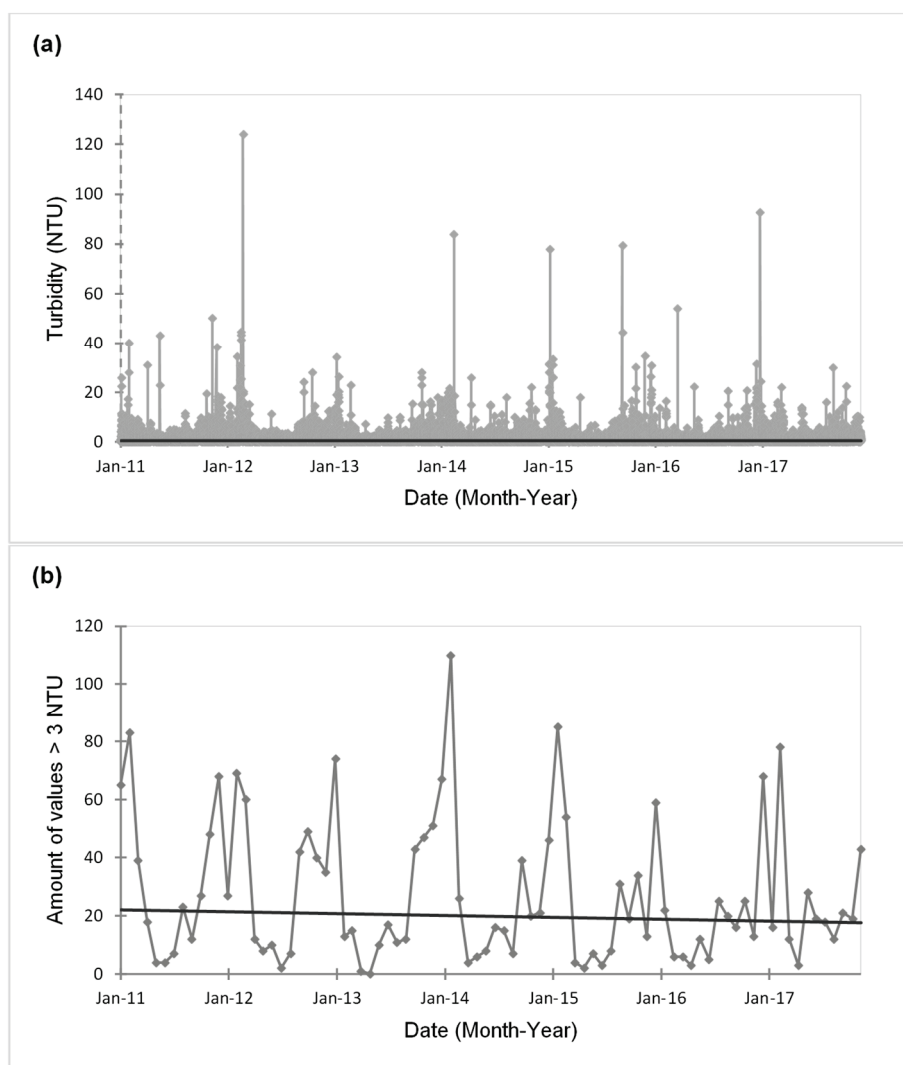


Figure 4. City of Salta. Mann–Kendall analysis for turbidity. (a) Analysis using all available turbidity data; (b) Amount of values greater than 3 NTU per month per year. The trend line is shown in dark grey.

This improvement in the initial phase of the WSP can be associated with the revision of the individual process steps in all plants, which means that the chlorination process was indirectly optimized. Control measures such as rotating guards, hiring more personnel in potabilization plants, and stricter water quality controls may have exerted a positive influence although no specific control measures were implemented for this variable. According to Table 4, anomalous chlorine levels represent 2% of the total chlorine data from 2011 to 2017, and Figure 6 shows a peak of 22 anomalous chlorine data in January 2015. This variable is relatively sensitive and must be carefully controlled, as any low chlorine concentration exposes a significant number of users to potential microbiological hazards.

No fluctuations were observed in *E. coli* during the study period. According to Table 3, anomalous *E. coli* values accounted for 0.42% of the total data from 2011 to 2017, and an

average of 1.7 anomalous values was observed during this entire period. Directly related control measures were taken, including restrictions to domestic animals and livestock, infrastructure improvements, increased security in catchment areas, continuous monitoring, and permanent staff at treatment plants, among others. *E. coli* is sensitive to chlorination, but high turbidity can also compromise the disinfection process [37]. Chlorination is also not sufficient to remove pathogens such as protozoa. Recent publications also indicate that evaluating the efficiency of water treatment based only on fecal indicator groups may misjudge the risk since other pathogens may be present even if coliform bacteria are not present [39]. In Salta Province, a quantitative microbiological risk assessment (QMRA) detected the presence of *Giardia* spp. in chlorinated drinking water, while *E. coli* was not present [37]. *E. coli* may not be the appropriate indicator to verify the effectiveness of WSP in our case study or in other cases where chlorination is well-controlled.

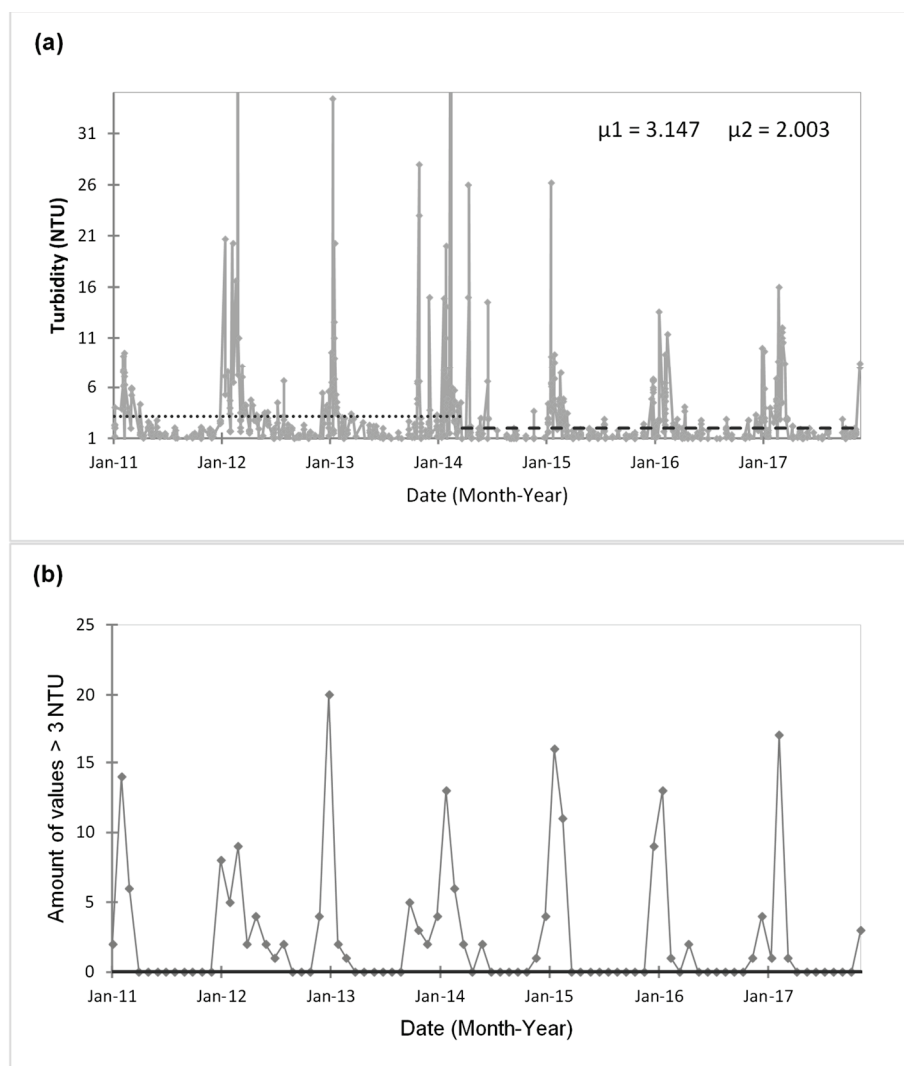


Figure 5. System No. 2. (a) Time-series analysis for turbidity values; (b) Number of values greater than 3 NTU per month per year. Significant shifts in the means values from the Pettit analysis are indicated by (dotted line) and μ_2 (dashed line).

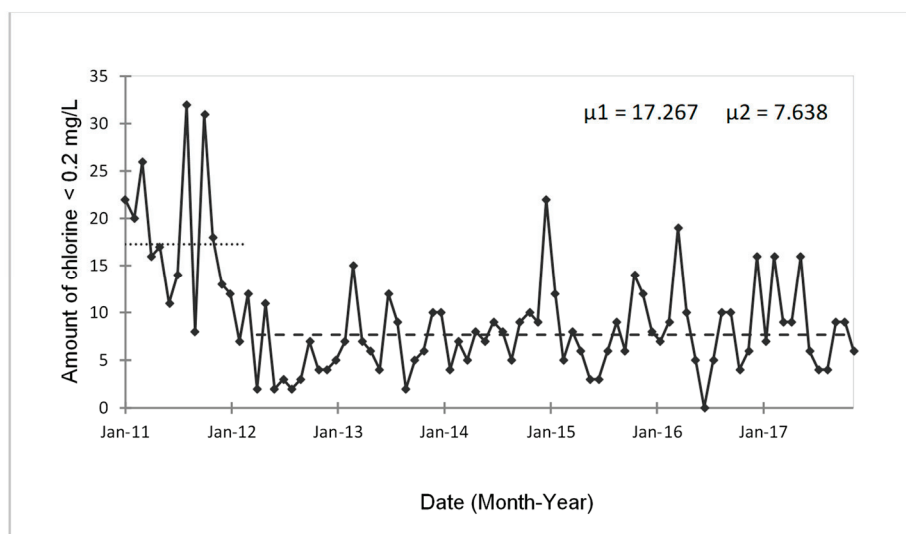


Figure 6. City of Salta. Pettit analysis for residual chlorine values. Significant shifts in mean values from Pettit analysis are indicated by (dotted line) and μ_2 (dashed line).

3.2.3. Limitations and Challenges

As mentioned in the introduction, there are previous studies that have examined the outcomes of implementing a WSP. However, the evidence is still limited, and there is no unified or standardized methodology for how the verification of a WSP should be conducted. Gunnarsdottir et al. [40] refer to a study in Iceland, one of the first countries to legislate the use of WSP, which allowed for the analysis of more than a decade of data on the impact of WSP. They compared sites with and without WSP implementation and also compared the values of variables before and after implementation. Significant compliance and public health impact benefits of WSP implementation were found. Setty et al. [41] conducted a verification of WSP and concluded that WSP improved water quality and led to a decrease in gastroenteritis at one of the sites studied. Setty et al. [26] also extended the earlier study using time series and recognized that implementation of a WSP is associated with improvements in water management and thus public health by controlling hazards such as precipitation events and turbidity spikes. For example, they found that at one study site, the rate of acute gastroenteritis increased by 9.6% for every 0.1 NTU increase in the monthly average, which is not comparable to the turbidity levels in Salta's baseline data. Recently, a time-series study was published [27,42,43] in which turbidity data from two years in Italy were analyzed to extrapolate with epidemiologic gastroenteritis events. What stands out in this study are the turbidity values observed in the time series, which in no case exceeded the value of 1 NTU. This situation is difficult to imagine in Salta. As can be seen in Figure 4, the turbidity levels in the rainy season exceed the maximum value of 3 UNT [33] established by law at the national level, and only 2% of the total complaints represent water quality complaints. A whole process of change of mentality is needed among the company, the regulators, and even the consumers so that the values registered in Salta are considered as serious as they really are. A significant decrease in customer complaints related to water quality was demonstrated in [28] during a 5-year WSP implementation. Although such benefits were not conclusively found in this study, it is possible to consider time-series analysis as an appropriate method to test the effectiveness of a WSP.

During the 5 years of the WSP in Salta, a certain degree of inertia was observed perhaps because the perceived decrease in risk was misinterpreted as continuous improvement. We believe that WSPs should focus more on recurring problems such as the presence of *E. coli*, poor chlorination, high turbidity, complaints, and water cuts. Control measures and monitoring should then be aimed at minimizing these specific hazards rather than focusing on general risk values.

The implementation of WSPs by water utilities is still voluntary, which is perhaps one of the limitations to its effective implementation. In addition, the WSP reveals current problems and also the need to allocate financial resources to implement control measures, some of which may not have been considered at the time of implementing a WSP. Decision makers should be careful to include the cost of complementary technologies to enable maintenance of services, as the impact on water quality and quantity may compromise water security [44]. One of the limitations of this study was the lack of easy access to the information due to the constant change of authorities in the company and some distrust of disclosing the results although this was later resolved, knowing that this scientific analysis can lead to addressing current problems. We believe that statutory regulation of WSP implementation would provide the necessary framework for effective implementation by utilities and provide the regulator with tools for decision making. It is not easy to obtain reliable information on the implementation of WSP by private or public utilities and not even by control authorities. Therefore, it is important to identify specific quantitative variables that may be useful in evaluating the effectiveness of these plans.

To date, there has been a decade of scientific contributions addressing various aspects of the water supply failure in Salta from a dual technical-socioecological perspective [2,37,38,45,46]. However, these results should go beyond the scientific milieu. Further research could address how previous scientific studies have impacted decision making or why they have not, considering that science-based decision making must be the way to effectively and sustainably address long-standing problems and water management.

It is important that decision makers do not minimize water supply problems, especially when these have health implications. The WSP serves to reveal the problems, but it is necessary to have quantitative parameters to demonstrate its effectiveness and not just subjective or questionable assessments. If this is not done, companies could be scrutinized by scientists and public opinion in the future.

4. Conclusions

In this paper, we present an assessment of the WSP for the city of Salta, Argentina, after 5 years of implementation. We reviewed the risk-assessment methodology adopted by a water utility in Salta, Argentina, and evaluated the implementation of control measures. We then verified the effectiveness of this WSP using a time-series analysis with data from consumer complaints and water quality indicators.

This allowed us to determine that although some control measures were implemented, and a reduction in risk values was observed, it was not possible to improve long-standing water supply problems, such as the number of consumer complaints or high turbidity levels during the rainy season. To address these problems, we suggest identifying the inherent problems of each water supply system and from there considering the necessary control measures to improve the service, especially if they are long-standing problems. In addition, evaluating the effectiveness of a WSP through a time-series analysis using as indicators the number of user complaints, turbidity levels, residual chlorine, and *E. coli* is a useful and objective tool for long-term evaluation of the effectiveness of a WSP.

We believe that stakeholder participation, distinct from water company membership, is necessary for objective and scientifically sound decision making. Regulation of WSP implementation would provide the necessary legal framework for efficient implementation by utilities and provide the regulatory authority with tools to monitor the achievement of efficient water service.

This study provides new insights into the implementation of a WSP, particularly in the effectiveness verify phase, and it is possible that future studies will be based on the methodology used here to further advance WSP implementation. We believe that these types of studies could be very useful for policy making because of their quantitative, independent assessment of water-management strategies of private or public companies.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w14192948/s1>, Table S1: Hazardous events, control measures and compliance of the control measures in 2016 for each system.

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Article

Evaluation and Mitigation of Flash Flood Risks in Arid Regions: A Case Study of Wadi Sudr in Egypt

Elsayed M. Ramadan ¹, Hossny A. Shahin ², Hany F. Abd-Elhamid ^{1,3}, Martina Zelenakova ^{4,*} and Hazem M. Eldeeb ¹

¹ Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt

² El-Arish High Institute for Engineering and Technology, El-Arish 45511, Egypt

³ Center for Research and Innovation in Construction, Faculty of Civil Engineering, Technical University of Kosice, 042 00 Kosice, Slovakia

⁴ Environmental Engineering Department, Faculty of Civil Engineering, Technical University of Kosice, 042 00 Kosice, Slovakia

* Correspondence: martina.zelenakova@tuke.sk; Tel.: +421-905-985-765

Abstract: Flash floods threaten the lives of people and properties in different regions around the world, especially in arid and semi-arid regions due to infrequent flood events. The current study aims to assess the geomorphological parameters of Wadi Sudr, South Sinai in Egypt to evaluate flash flood risks and provide adequate mitigation methods. This study presents an integrated method that combines geographic information system (GIS) and watershed modeling system (WMS) with HEC-HMS to visualize and assess flood events in the study area. Different morphologic parameters of the watershed were determined, including linear, areal, and relief parameters. GIS was used to analyze the satellite images and determine the characteristics of the valley to get the extension and number of stream orders in the valley, then WMS was used to estimate rainstorms and basin characteristics, as well as estimate the amount of rain that causes flooding. HEC-HMS program was used for hydrological demonstration and precipitation overflow estimation. The morphometric analysis provided a quantitative portrayal of the Wadi Sudr watershed. Wadi Sudr has 4029 streams connected with seventh order of streams spread over an area of 547.45 km². Based on the results of morphologic and hydraulic parameters of the watershed, two locations of protection dams were suggested. A comparison between the two locations was made to select the best location based on some criteria, including storage capacity, water depth behind the dam, width and shape of the valley, and the area covered by water stored in the reservoir. The comparison between the two locations showed that the first location is more appropriate for dam construction based on the examined criteria. The valley shape in the first location is more regular than in the second. The first location provided higher storage capacity and water depth in front of the dam than the second. The area covered by water and the width of the valley is less than the second. The stability of the dam at the first site could be higher and the cost of construction could be less than the second due to these reasons. A comparison was made using the weighted linear combination (WLC) method, which consists of 13 criteria to determine the suitability index (SI) in order to select the best location from the proposed locations. SI proved that the first location is better than the second. The designed dam in the selected site could be cost-efficient to protect the study area from flood risks and harvesting water that can be used in different purposes. This methodology can be applied in different areas for mitigating flash flood risks.

Keywords: flash floods; flood protection; morphologic parameters; Wadi Sudr; GIS; WMS; dams

1. Introduction

Flooding is one of the most dangerous phenomena that have many dangerous effects on rural and urban areas. Floods may destroy buildings, threaten the lives of people and

living creatures, cut roads, and destroy infrastructures. Evaluation and mitigation of flash floods effects is a crucial issue to protect properties and the lives of people. Egypt's northern coasts and the Sinai Peninsula are the parts of Egypt that has been affected by flash floods in the last decades. One of the most significant Wadies in Sinai is Wadi Sudr that has a significant tourist city.

A number of studies have been carried out to evaluate flash floods in different Wadies in Sinai including Wadi Sudr. Fathy et al. [1] evaluated different hydrologic models to obtain the best model that simulates runoff hydrograph for Wadi Sudr, Sinai, Egypt. The watershed modeling system (WMS) package was used for the comparison between three different models, including lumped (HEC), semi-distributed (HEC-HMS), and distributed (GSSHA). It was found that there is a great agreement between distributed model outputs and the corresponding streamflow measurements. The integration of hydrological model with numerical weather prediction (NWP) model has been applied for flash flood forecasting. Giannaros et al. [2] used the weather and research forecasting (WRF) mesoscale atmospheric model and the integrated multi-satellite retrievals for global precipitation measurement (GPM-IMERG) algorithm. The hydrologic engineering center hydrologic modeling system (HEC-HMS) was also used for estimating streamflow in the watershed. Yucel [3] investigated the hydrological response of the Ayamama Basin to the precipitation event using the precipitation forcing in the HEC-HMS model to check the capability of estimated precipitation products from nowcasting (radar and HE) and forecasting systems (WRF) against observed precipitation (rain gauge). Lotfy [4] found that the rainfall gauge network is a key driver for hydrologic modeling to evaluate flash flood runoff. Four scenarios for the creation of rain surfaces and their effects on the estimated runoff of Wadi Sudr in the Sinai Peninsula were studied. Dewidar [5] used GIS to determine the morphometric parameters of the Wadi El-Gemal Basin on the Red Sea coast. In addition, Abdel-Latif and Sherief [6] used geographic information systems and remote sensing to separate new waste organizations with more subtleties to prepare regular peril guides of the channel Sudr and watercourse Wardan, which are almost opposite on the eastern side of the Gulf of Suez, Egypt.

Another study was conducted for the Ras Sudr area by El-Bihery [7]. The study showed that the Quaternary aquifer is the most prospective in the Ras Sudr area (the delta of Wadi Sudr). MODFLOW code was applied to designing a three-dimensional groundwater flow model. SEAWAT was also applied to simulate variable-density flow and seawater intrusion from the west. El-Behiry et al. [8] prepared a quantitative investigation of geo-morphometric boundaries to outline watershed of the Wadi Ghoweibba Basin in the Ain Sukhna zone, western side of the Gulf of Suez, Egypt. It was found that the quantitative analysis of the computed geomorphometric parameters of the Ghoweibba Valley Basin was used to decipher the flood risk areas and to create an effective scheme to mitigate the risks. El-Sayed and Habib [9] revealed that the Sinai Peninsula falls within an arid belt that crosses northern Africa and southwestern Asia. Several flash floods were recorded in south Sinai, which resulted in significant infrastructural damages, inhabitants' displacement, and sometimes loss of lives. The study examined the utility of a physically based distributed hydrologic model to simulate rainfall-runoff response in Sinai. Data were collected and compiled from the available rain gauges in the studied catchments. Overland hydraulic properties and soil hydraulic parameters were varied according to combined classifications of soil type and land-use maps. Results showed suitable agreement between GSSHA simulated hydrographs and streamflow measurements.

Some studies have been carried out to evaluate flash floods around the world such as Shaikh and Farjana [10], which utilized GIS to examine the Eru stream Basin, a subwatershed of Mahi waterway, Rajasthan, India. In addition, Soni et al. [11] used GIS in the waste depiction in Rachhar Nala, Anuppur District of Madhya Pradesh. Thakur et al. [12] presented a morphometric examination of the Balawal watershed in Jammu Province of Jammu and Kashmir State to assess the waste boundaries and basin qualities. Abdul Rahaman et al. [13] studied the integration of using GISs in the evaluation of the morphological qualities

of watersheds with a multi-standards dynamic (MCDM) through a fuzzy logic chain of importance procedure to decide its flash flood prioritization. Javed et al. [14] considered the morphometric and land-use qualities for the prioritization of sub-watersheds utilizing remote sensing and GIS strategies, it was concluded that the sub-watersheds were classified into three categories as high, medium, and low in the order of priority to the conservation and management of natural resources. Moreover, in the last decades despite the improvements in flood mitigation measures and technological advancements, floods continue to endanger human lives, especially when ephemeral streams cross-urban centers (Chatzichristaki et al. [15]; Diakakis et al. [16]). Omran et al. [17] examined the flood hazard map in the Dahab Basin and it was discovered that 34% of the all-out subbasins in the Dahab Basin had a high risk of flooding, and 60% of all subbasins have a medium flood hazard. Negm et al. [18] concluded that the ecological security of neighborhoods from the danger of abrupt flooding requires a fundamental assessment of pinnacle release and postpone time. The created conditions permit the expectation of deferring time with an exactness of 7% for mistakes and pinnacle release with precision under 14% for a blunder, permitting security of Wadi Sudr from the dangers of fast flooding.

Floods are a genuine, grievous occasion that can happen anywhere. Regions inclined to flooding and waterlogging ought to be recognized to foresee spatial circulation. To take care of this issue and advance the appraisal strategies, a random forest-based model was proposed for the investigation as per the hypothesis of the flood system by Wang et al. [19]. Stefanos and Stathis [20] utilized the formation of the investigative chain of importance and GIS cycle to survey flood possibility. Morphometric and hydrographic properties of watersheds were determined. Nektarios and George [21] built up a flood executives plan comprising of two parts: a proper flood boarding procedure and the distinguishing proof of flood hazard regions. The investigated region was partitioned into five subregions with various degrees of flood hazard from extremely low to exceptionally high. Gabr and El Bastawesy [22] analyzed the issue of blaze floods in the watersheds of the oil creation zone in Ras Sudr. Abd-Elhamid et al. [23] used GIS and WMS for evaluating flood risks in the area located at a distance of 7.50 km from El Gouna city along the Red Sea and east of Hurghada–Al Ismaileya road. The results indicated that the site is exposed to high flash flood risk and protection work is required. They suggested using three dams and four channels to protect the area from flood risks. Abd-Elhamid et al. [24] examined the effect of using different digital elevation models (DEM) from different websites on the accuracy of watershed management. Many websites offer DEM, including SRTM, GTOPO30, and ASTER GDEM, however the accuracy of each one varies, and choosing a tiny DEM size also yields accurate information, but the analysis takes a while. To evaluate these models' correctness and choose the most accurate one for the application, three case studies were examined in Sinai.

Some techniques have been used to mitigate flash flood risks. Orabi et al. [25] identified four unique drainage basins for catchment areas in western central Sinai to consider flash flood risks. The implemented technique discovered that hydrological and morphometric parameters play essential roles in contributing factors to flash floods. The employed method revealed that the hydrologic and morphometric parameters play crucial roles in contributing to flash floods. Flood risk management relies heavily on the integration of hydrologic indices, sediment transport, and topographic wetness indices with morphotectonic characteristics to provide sedimentation linked to flash floods. Runoff water harvesting is regarded as a crucial method for solving water scarcity in arid and semi-arid settings, according to Elewa et al. [26]. To use a multiparametric decision spatial model, eight effective RWH characteristics were selected: the overland flow distance, yearly flood volume, drainage density, maximum flow distance, infiltration number, watershed slope, watershed area, and watershed length. The watershed was divided into five categories of RWH potential on the ensuing MPDSM map, ranging from extremely low to very high. Abd-Elhamid et al. [27] identified water scarcity in arid and semi-arid regions as representing a significant obstruction to social and economic development. Integrated

hydrological models, including geographic information systems, watershed modeling systems, and groundwater modeling systems, were used. The results showed that the dams could collect about 160.72 million m³ of rainwater that can be stored or recharged into groundwater aquifers. According to Fathy et al. [28], roadways in arid areas are particularly vulnerable to flooding damage. This necessitates a thorough examination of the amount, timing, and direction of the flood so that the appropriate safety precautions may be designed. This can be used to create flood mitigation strategies to safeguard the roadways from flood risks. To reduce the risk of flooding in the area, a protection system of seven channels and two culverts was suggested.

This study aims to evaluate and mitigate flash floods effects in Wadi Sudr, Egypt, as the Wadi Sudr region is exposed to flash flood events that cause disasters and destruction in the region. The methodology of this research depends on integration between remote sensing based on analysis of satellite images to predict stream morphometric parameters for the Wadi and using numerical models such as watershed modeling system software (WMS) to estimate the expected volume of runoff and select the more appropriate locations for flood protection. The study is based on evaluating the number of floods that occurred due to the rainstorm, reaching the best places for harvesting torrential waters, preserving lives and properties, proposing and selecting the best sites for construction of protection dams, and determining the characteristics of the dams according to the study results of the expected flood volumes.

2. Study Area

2.1. Location and Land Use

Ras Sudr is an Egyptian city located on the Gulf of Suez on the coast of the Red Sea and belongs to South Sinai Governorate. One of the most significant wadies and waterways in the Sinai Peninsula is Wadi Sudr, which is located in the southwest of the peninsula between Latitude 29°35' and 29°55' N and Longitude 32°40' and 33°20' E. Wadi Sudr drains water into the Gulf of Suez near the town of Ras Sudr and has a total area of 550 km². One of the most significant valleys in the Sinai Peninsula is Sudr Valley (Figure 1). Ras Sudr city is one of the major tourist destinations, which is located across from Wadi Sudr. A 95 km-long beach offers swimming and other water sports in Ras Sudr. Sinai Bedouins from Wadi Sudr regions live in the bulk of the town and its surrounding areas. The primary north-south route divides the two residential neighborhoods that makeup Ras Sudr. Workers, who primarily come from Egypt's Nile Delta and Nile Valley governorates, are housed locally on one side. The other is made up of second homes for vacations and private villa dwellings for professionals, most of whose owners are from the Egyptian capital "Cairo".

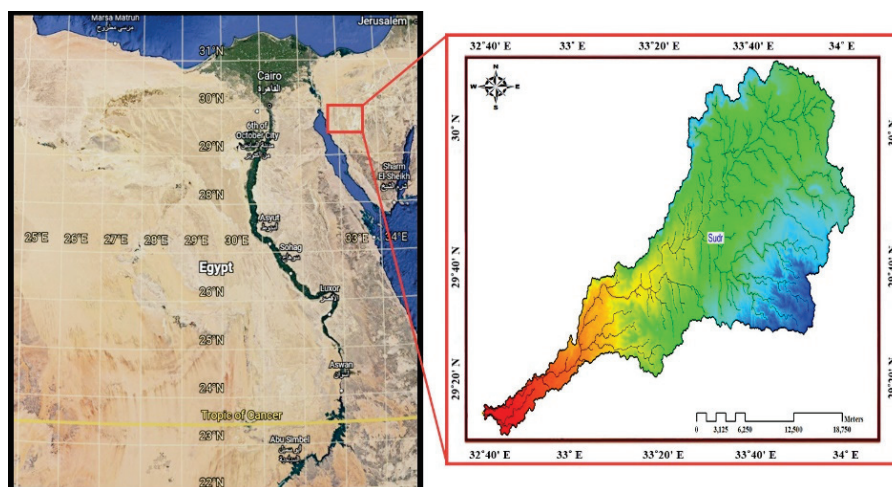


Figure 1. Location map of Wadi Sudr.

2.2. Climate Conditions

The Sinai Peninsula has a climate that is comparable to other desert areas across the world. It experiences severe aridity, long, hot, and dry summers, and mild winters [6]. During the winter, some sections of Sinai experience brief but significant rainfall, which causes Wadi beds to overflowing and occasionally creates flash floods that inflict damage to roads and occasionally even human lives. In Wadi Sudr, the seasons are lengthy in the summer (April to October) and short in the winter (November to December), with a transitional period from January to March [29]. The evaporation in this region is highly important since, depends on variables including temperature, relative humidity, wind speed, plant cover, and solar radiation. Evaporation values are typically higher than precipitation values. The rate of evaporation varies depending on the specific area [30]. Arid weather is defined as having a relative humidity of less than 50%, semi-arid weather as having a relative humidity between 60% and 70%, and humid weather as having a relative humidity of greater than 70%. Therefore, Wadi Sudr is regarded as a semi-arid area.

2.3. Geological Setting of Wadi Sudr

Some scientists have investigated the geology of Sinai and Wadi Sudr. According to previous studies, geological maps of Sinai, and the geological survey, the geological formation of the study area is depicted in Figure 2 and categorized as follows:

- Wadi floors include sediments from the Quaternary age. These deposits primarily consist of soft gravel. The origin of these deposits, the slope, the basin size, and the width of the Wadi all affect how they vary from one Wadi to the next.
- Salt pan deposits from the Quaternary age have intertwined with the playa. The primary constituents of sabkha sediments are typically carbonates, evapotranspiration, fluvial, aeolian, and marine detritus, which are occasionally cemented with carbonate or gypsum.
- The primary channels of the examined wadies are covered in Pleistocene and Holocene sediments, which constitute Quaternary deposits. Alluvial, Wadi, and Sabkha deposits make up most of these deposits.
- Sandy shales with intercalations of phosphatic marl and limestone make up the Cretaceous Matulla Formation.
- Chalk and dolomitic limestone are the main components of the Sudr formation, which is of Cretaceous age.
- The Gharandal group is represented by the Uyun Musa Formation (Middle-Lower Miocene age), which is composed of green gypsiferous fossiliferous clays intercalated with sandstones and marls, and the Sumar Formation (Lower Miocene age), which is represented by gypsiferous yellowish green shale and gray to white intercalation with a thin.
- The Kareem Formation (Middle Miocene age), which consists of clastics with interbedded anhydrite and sporadic limestone, the Belaim Formation (Middle Miocene age), which consists of intercalation of evaporates and marl, and the Hammam Phrayuon Formation (Middle Miocene age), which consists of two main facies, are the representative formations of the Ras Malab group. The first is calcareous facies made up of argillaceous limestone with interbeds of shale and marl, while the second is shaly facies made up of shale, marl, and sandstone. Anhydrite shales and a few trace amounts of sand make up the South Gharib Formation, which is of the Upper Miocene age. Vapors with clastic intercalation make up the Zayt Formation.
- Extrusive basaltic rocks (Olivine basalt).
- Chalky limestone with flint bands and nodules at the base and thin, succeeding chert bands on top make up the Egma Formation (Eocene age).
- Paleocene-era Esna Formation is composed of a grayish-yellow marly limestone band in the center of a dark-green shale matrix. It is layered between the Thebes Formation and the Sudr Formation.

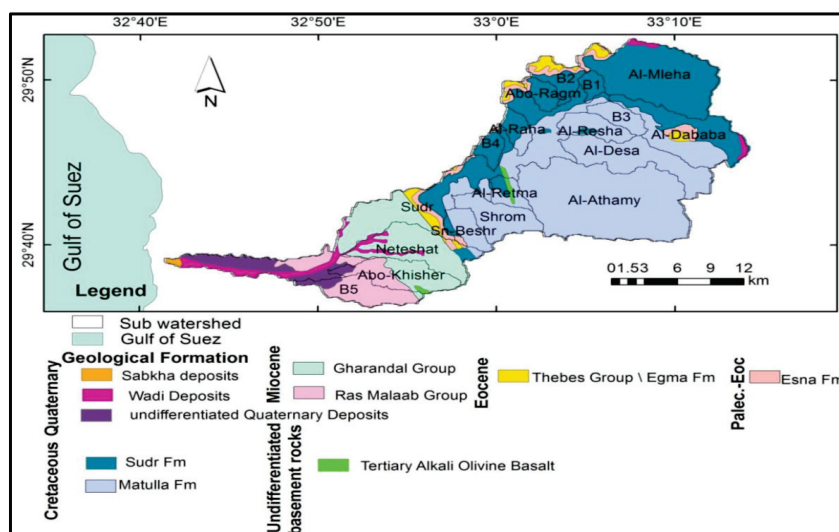


Figure 2. Geological map of Wadi Sudr [30].

3. Methodology

This study's main goals are to create a new stream network, demonstrate morphometric analysis of the watershed, choose an appropriate location for a protection dam, and design the necessary dams to reduce the danger of flooding in the study region. To achieve these goals the study has been carried out in two steps: determine morphologic parameters of the watershed and analysis of the study area then design the protection dams. The following sections describe the steps followed to accomplish these goals.

3.1. Morphologic Analysis of the Study Area

The morphological parameters of the investigation zone were investigated utilizing a digital elevation model (DEM) with a resolution of 15 m obtained from SRTM (shuttle radar topography mission data) that was transferred by WMS, which were accordingly refined by geological lines, spot statures, and streams. The top sheet of scale (1:25,000) was sent out to a geographic information system (GIS), climate (Arc GIS 10.5 programming). Guides have been changed over to universal transverse Mercator (UTM) map view and WGS 1984 to be viable with various GIS topical layers. Then a drainage network was sent out to GIS to characterize stream order and determine the length and number of each stream order for all basins.

Morphometric properties for the watershed were determined based on the equations recommended by Horton [31,32] and Strahler [33,34]. Furthermore, Faniran [35], Schumm [36], and Miller [37] were summarized in Table 1. Different morphometric parameters were characterized into three types:

1. Linear parameters of the watershed: stream order (Nu), bifurcation ratio (Rb), mean bifurcation ratio (Rbm), stream length (Lu), mean stream length (Lsm), and stream length ratio (RI).
2. Areal parameters of the watershed: drainage density (Dd), stream frequency (Fs), texture ratio (Dt), infiltration number (If), length of overland flow (Lg), elongation ratio (Re), circularity ratio (Rc), and form factor ratio (Rf).
3. Relief parameters of the watershed: basin relief (H), relative relief (Rhb), relief ratio (Rh), and roughness number (HD).

Table 1. The formulas used for the computation of morphometric parameters [30].

Property	Morphometric Parameters	Formula	Author
Linear	Stream order	Hierarchical rank	Strahler (1964)
	Bifurcation ratio (Rb)	$Rb = Nu/Nu + 1$	Schumm (1956)
	Mean bifurcation ratio (Rbm)	Rbm = Average of bifurcation ratios of all orders	Strahler (1964)
	Stream length (Lu)	Length of the stream (km)	Horton (1945)
	Mean stream length (Lsm)	$Lsm = Lu/Nu$, km	Strahler (1964)
	Stream length ratio (RI)	$RI = Lu/Lu - 1$	Horton (1945)
Areal	Drainage density (Dd)	$Dd = (\Sigma Lu/Au)$ km/km ² where Au = area of the basin (km ²)	Horton (1932)
	Drainage texture (Dt)	$Dt = \Sigma Nu/P$ where P = perimeter (km)	Horton (1945)
	Stream frequency (Fs)	$Fs = \Sigma Nu/Au$	Horton (1932)
	Infiltration no. (If)	$If = Dd \times Fs$	Faniran (1968)
	Length of overland flow (Lg)	$Lg = 1/Dd \times 2$ km	Horton (1945)
	Form factor (Rf)	$Rf = Au/Lb^2$	Horton (1932)
	Elongation ratio (Re)	$Re = 2\sqrt{(Au/\pi)/Lb}$ where $\Pi = 3.14$	Schumm (1956)
	Circularity ratio (Rc)	$Rc = 4\pi Au/P^2$	Miller (1953)
	Relative relief (Rhp)	$Rhp = H \times (100)/P$ where H = maximum basin relief	Melton (1958)
Relief	Relief ratio (Rh)	$Rh = H/Lb$ max	Schumm (1956)
	Ruggedness number (HD)	$HD = H \times Dd$	Strahler (1956)

These parameters were determined using GIS. The different formulas used for the calculation of morphometric properties are shown in Table 1.

Through the upgraded version of WMS, five maps were downloaded that help in accurate analysis of the area and these maps are: (1) world imagery, (2) world topography, (3) STRM worldwide elevation data (3-arc second resolution), (4) global land cover, and (5) harmonized world soil database V 1.1, besides specifying sufficient information about the zone such as the universal transverse Mercator (UTM) map show and WGS 1984. The primary drainage module of WMS 11.0 programming was used to extract the drainage network, followed by its submodules using the topographic parameterization program (TOPAZ) program (AQUAVEO, 2019). To compute stream bearings and stream collections for use in basin elaboration with DEMs, an altered version of this application is distributed with the WMS programming.

The SRTM and land-use data were combined to create the DEM with a 15 m resolution. As a philosophy, we decided on the SCS method, composite curve numbers (CN) for invasion limit, and spillover. The amount of rainfall that falls on the basin has been entered, and estimates of the composite bend (CN) based on the quality of the soil (Soil), land use, and cover have been made. In addition, determine the concentration period, compute the lag period, and determine the slope. Since the Wadi Sudr Basin's CN value was 94, precise information could be provided regarding the time the stream peaks (time of peak), the amount of water released per second (peak releases), and the total volume of moving water in the basin.

3.2. Selection of the Protection Dam Location and Design of the Dams

This section presents the criteria for selecting the location of the protection dam. The location of the dam was chosen according to some criteria. The most important one is the dam located in the narrowest area in the course of the valley. Moreover, the proposed location provides the largest capacity for the amount of stored water, which reduces the total construction cost of the dam. Furthermore, topographically, the dam location has the natural shoulders to provide adequate dam support. Consequently, two places were chosen

that met these conditions. The dam was designed, and the amount of stored water and the storage capacity that accommodates the size of the flood in the area were investigated. Furthermore, a comparison was made between the two proposed places that comply with the site conditions and specifications.

4. Results and Discussion

4.1. Morphologic Parameters of Wadi Sudr

The morphometric analysis was calculated using the suggested methodology for the current study area. The study provided information on the basin's drainage features and runoff potential. The following sections summarize the findings for the three different watershed parameter groups.

4.1.1. Linear Parameters of the Watershed

The stream length (Lu), bifurcation ratio (Rb), and stream order (Nu) are the main linear watershed parameters. Figure 3 depicts the watershed's stream order for the Wadi Sudr Basin. The number of streamlines inside a watershed for a certain class of stream order, or the number of stream parts of various orders, is known as the stream number (Nu) [34]. There are 4029 streams in Wadi Sudr that are related to the seventh order of streams, covering an area of 547.45 km². A number of streams of 3118, 693, 166, 40, 9, 3, and 1 from the first through seventh orders were observed. As indicated in Table 2, Wadi Sudr contains the seventh-order standard.

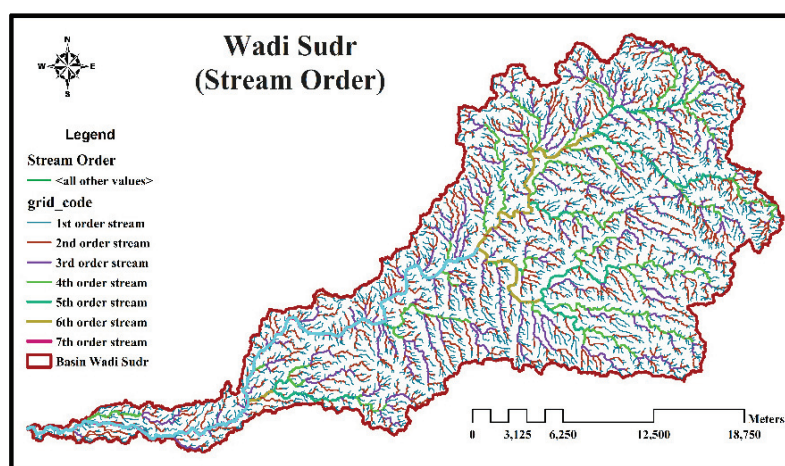


Figure 3. Wadi Sudr sub-watersheds and their streams orders.

Table 2. Stream order, stream number, stream length, and bifurcation ratio for Wadi Sudr.

Wadi Sudr Watershed					
Stream Order	Stream Number (Nu)	Stream Length (Lu) (km)	Mean Stream Length (Lsm) (km)	Stream Length Ratio (RI)	Bifurcation Ratio (Rb)
1st	3118	1019.604	0.327	0.000	4.500
2nd	693	518.729	0.748	0.509	4.175
3rd	166	261.664	1.576	0.504	4.150
4th	40	141.548	3.539	0.541	4.444
5th	9	49.389	5.488	0.349	3.000
6th	3	28.181	9.394	0.571	3.000
7th	1	48.778	48.778	1.731	0.000
Mean Bifurcation Ratio (Rm)					3.324

According to Horton [32], stream length is the total length of all streams that appear to have the same stream order. The total length of the stream, divided by the number of

portions in that order, is the mean stream length. The main Sudr subwatershed's highest and lowest orders could both be shown to have different mean stream lengths. In the first stream order, the mean length value was 0.327 km, whereas it was 48.778 km in the fifth order. The shift in geological height and the inclination of the area, where it was held in place by cellar rocks, may have caused the deviation. Additionally, it was found that the first, second, third, fourth, fifth, sixth, and seventh stream orders, separately, have normal current lengths in Wadi Sudr of 0.327, 0.748, 1.576, 3.539, 5.488, 9.394, and 48.778, respectively as indicated in Table 2. The stream length ratio was defined by Horton [32] as the ratio of the average stream length of the next lower order ($u - 1$) to the typical stream length of order (u). According to Table 2, the stream length ratio for Wadi Sudr changed from 0.349 to 1.731.

According to Strahler [34], the bifurcation generally occurs in watersheds where the geologic formations do not bend the waste example, between 2.0 and 5.0. Additionally, basins with low bifurcation ratios are spherically perfect, allowing spillover to pause while framing a dramatic peak of runoff [34]. In Wadi Sudr, the effect of the bifurcation ratio was more than 2. Wadi Sudr Basin's bifurcation proportion shifted from 3 to 4.5, showing that the geologic features were not bent to fit the waste scenario. According to Table 2, the bifurcation ratio for the first, second, third, fourth, fifth, and sixth stream orders in Wadi Sudr was 4.500, 4.175, 4.150, 4.444, 3.000, and 3.000, respectively. The average bifurcation proportion in Wadi Sudr was 3.324, demonstrating that the trash example was not twisted by the geologic formations.

4.1.2. Areal Parameters of the Watershed

The watershed areal parameters include a number of parameters that are analyzed in this section. Drainage density (Dd) was presented by Horton [32], as the proportion of absolute stream length inside a basin to the basin zone. It gives a thought regarding the physical properties of the basic rocks in the investigation territory. According to Table 3, drainage density for Wadi Sudr is 3.777 km^{-1} showing delicate inclines, low precipitation, and penetrable, cracked, profoundly jointed bedrock. Smith [35] categorized drainage texture ratio (Dt) and seepage surfaces into five classes, extremely coarse (<2), coarse (2–4), moderate (4–6), fine (6–8), and exceptionally fine (>8). The seepage surface relies on various normal factors. The waste surface for the Wadi Sudr watershed is 16.878. This worth is higher than 8, showing an extremely fine drainage texture. Horton [31] characterized stream frequency (Fs) as the number of streams per unit region. It may be seen from Table 3, where as the estimation of the stream recurrence of Sudr Valley was 7.361 km^{-2} and the worth was high, which demonstrates that the stream recurrence (Fs) increments with the expansion in seepage thickness (Dd), showing the dangers it might occur here.

Table 3. Morphometric areal aspects of Wadi Sudr.

Areal Parameters	Value
Drainage Density (Dd) km^{-1}	3.777
Drainage Texture (Dt)	16.878
Stream Frequency (Fs) km^{-2}	7.361
Infiltration Number (If)	27.803
Length of Overland Flow (Lg) km	0.132
Form Factor (Rf)	0.186
Elongation Ratio (Re)	0.487
Circularity Ratio (Rc)	0.121

Infiltration number (If) was characterized by Faniran [35] as the result of seepage thickness and stream frequency and given a thought regarding the invasion qualities of the watershed. The higher the infiltration number, the lower will be the invasion, and subsequently, the higher will be surface overflow. It was likewise discovered that the invasion number in Wadi Sudr had an estimation of 27.803, as shown in Table 3, as

the worth was high, which additionally had the higher estimations of drainage density, showing a high spillover plausibility and low groundwater energizing probability. Length of overland flow (L_g) is the length of water over the ground before it gets gathered into distinct stream channels. Basins of long overland streams actuate high penetration and are generally safe from hazard flooding. The length of an overland stream for Wadi Sudr was 0.132 km. Form factor ratio (R_f) was defined by Horton [31] as the proportion of the region of the basin to the square of the length of the basin. For a roundabout basin, the worth ought to be more prominent than 0.78. Wadi Sudr watershed had a less form factor of 0.132, demonstrating extended shape. The structure factor of Wadi Sudr demonstrates that the basin will have a complement pinnacle of a stream for a longer span.

Elongation Ratio (R_e) is a parameter that shows the zones have high invasion limits and low spillover. These qualities can be assembled into three classifications in particular: round (>0.9), oval (0.9 to 0.8), and less stretched (<0.7) [38]. The fundamental Sudr watershed had a lower prolongation ratio of 0.487 showing lengthened shape. Circularity ratio (R_c) estimation, for the most part, changes from 0 (a line) to 1 (circle). The higher the estimation of circularity proportion, the more the round state of the basin and the other way around [10]. The circularity ratio for Wadi Sudr was 0.121, demonstrating an extended shape.

4.1.3. Relief Parameters of the Watershed

The watershed relief parameters are analyzed in this section. Maximum basin relief (H) is the most extreme vertical separation between the least and the most elevated purposes of the basin [39]. For Wadi Sudr, the most extreme height is 870 m (a.m.s.l) and least rise is 11 m (a.m.s.l). Moreover, the normal basin elevation esteem in the examination territory was 859 m. This worth was acquired from the investigation of rises in the examination region in the watershed modeling system (WMS) program, as shown in Figure 4.

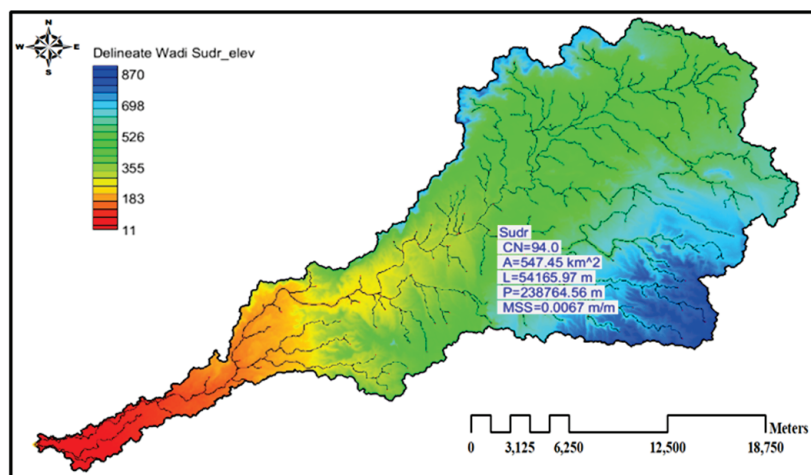


Figure 4. Elevations of Wadi Sudr from the WMS program.

Relative relief (R_{hp}) was characterized by Schumm [36] as the proportion of most extreme basin alleviation (H) to the edge of the basin. Relative relief for the Sudr watershed was 0.360, as shown in Table 4. Relief ratio (R_h) was characterized by Schumm (1956) as the proportion of all-out help of watershed and level separation along with the longest component of the basin corresponding to the vital drainage line. Likewise, the alleviation proportion for Wadi Sudr is 0.0159. From Table 4, it has been seen that serious extent of the relationship between high help, high stream channel inclines high, waste recurrence, and high stream recurrence showing high releases in brief length. Ruggedness number (HD) was characterized by Strahler [40] as the result of the most extreme watershed alleviation and seepage density. It is found that the roughness number of Wadi Sudr is high, at

3,244,443, because of the high waste density, high estimations of seepage density and greatest basin alleviation show very high estimations of HD.

Table 4. Morphometric relief parameters of Wadi Sudr.

Watershed	Total Relief (m)	Relative Relief (Rhp)	Relief Ratio (Rh)	Ruggedness Number (HD)
Wadi Sudr	859	0.360	0.0159	3244.443

4.2. The Drainage System Characteristics of Wadi Sudr

Precipitation is the main factor affecting the hydrological model. The work in this study was performed with the value provided by Sonbol et al. [41], which was derived from the storm that occurred in 1991 in the region, and the result of rainfall was 34.5 mm. Based on the type II 24 h precipitation model, which was designed to model the precipitation distribution (accumulated precipitation) within a 24 h WMS over the basin and the accumulated runoff, the general shape of Wadi Sudr was determined as shown in Figure 5.

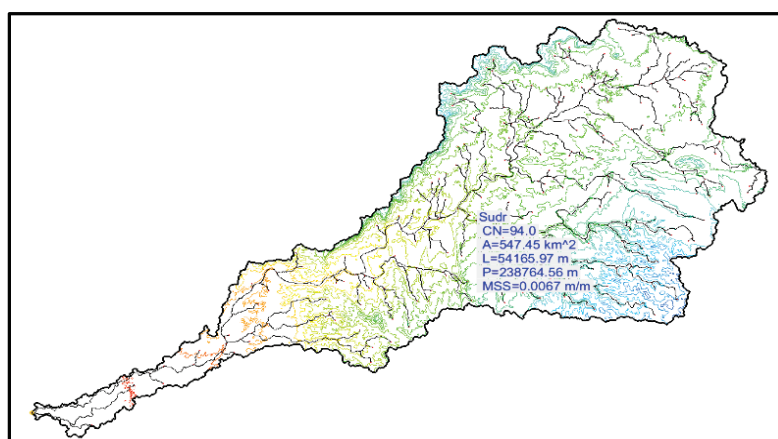


Figure 5. The general shape of Wadi Sudr.

Basin's viability can be evaluated through its drainage system morphometric boundaries. Table 5 shows the essential morphometric boundaries considered. The morphometric boundaries showed that the total area of the catchment is 547.45 km². The entire territory was viewed as a solitary basin with a stretched shape. The normal overland incline suggested the common desert attributes of the study area that quickens overland stream over little separations. The basin rise from the most upstream edge to the source fluctuates from 11 to 870 m. The normal slope of the main channel is 0.0067 m/m.

Table 5. The drainage system characteristics of Wadi Sudr.

Parameter	Area (km ²)	Length (m)	Precipitation (mm)	Basin Slope (m/m)	Curve Number	Lag Time (h)
Wadi Sudr	547.45	54,165.97	34.5	0.0067	94	4.673

In this study, a simulation of rainfall was carried out with multiple possibilities representing the current reality according to the rainfall value over the area in Wadi Sudr, which is 34.5 mm. The results of the period of hydrograph produced by HEC-1. For the hydrographic output of about 11.267 million m³ with a peak flow of 361.20 m³/s at a peak time of 1020 min, as shown in Figure 6. This hydrograph was calibrated and compared with Sonbol et al. [41], results where the value of the CN was close and the flux difference was about 6.5%, which is an acceptable percentage of acceptance error, as shown in Figure 6.

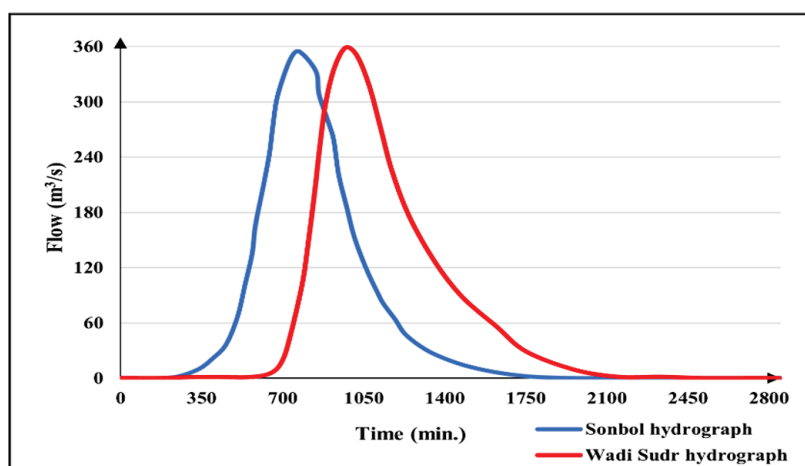


Figure 6. Comparison between Sonbol and WMS outlet hydrographs at Wadi Sudr.

4.3. Analysis of the Dam Site Based on Morphological Properties of the Watershed

This stage of the study aims to analyze the location of the dams based on some criteria, including the width and the shape of the valley at the dam location, the storage capacity of the dam, the water depth behind the dam, the covered area by the reservoir, and the total construction cost. Based on the morphological analysis of the watershed, two locations were selected for the dam that met these conditions, as shown in Figure 7. Then the dam was designed, and the storage capacity that accommodates the flood in the area was calculated. Furthermore, a comparison was made between the two proposed locations that comply with the site conditions and specifications.

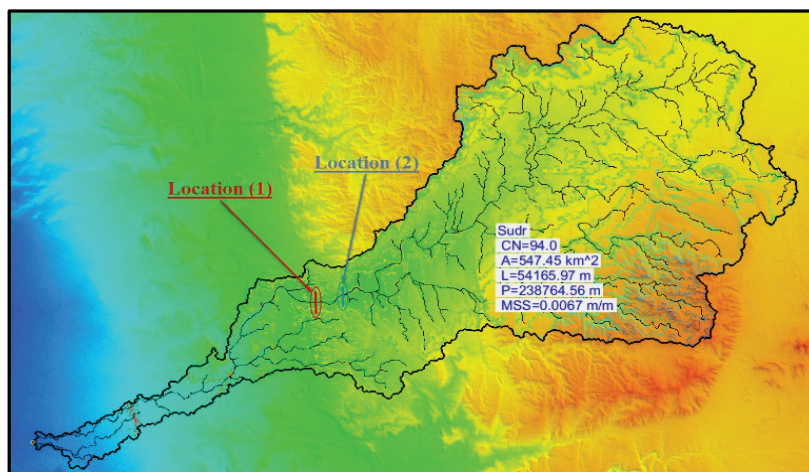
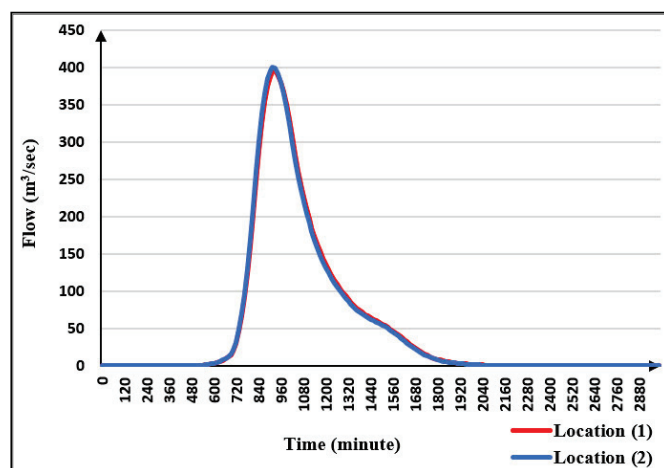


Figure 7. Selected locations for proposed dams.

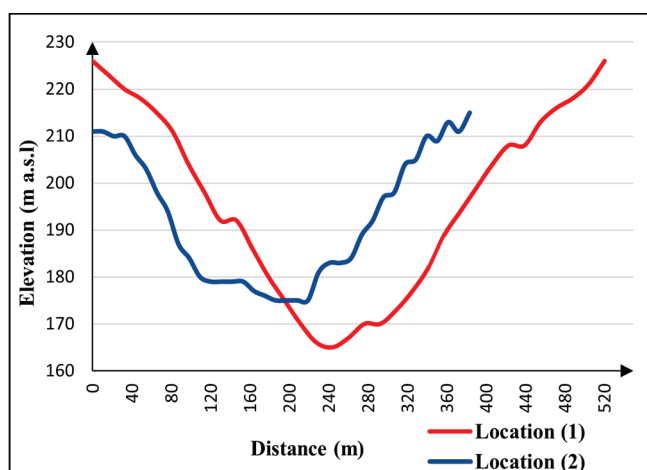
WMS is used for rainfall data analysis through the required inputs, including the amount of precipitation, curve number, and delay time required for the arrival of the flood to the end of the valley. The computed parameters for the two proposed dam locations are shown in Table 6, which include peak flow, time, and volume of flow. The hydrograph produced by HEC-1 for the two proposed dam locations is shown in Figure 8. For the first location, the volume of the flow was 9.375 MCM with a peak of 396.39 m³/sec at a time of 930 min. However, for the second location, the volume of flow was 9.323 MCM with a peak of 401.17 m³/sec in a time of 915 min.

Table 6. The dams parameters of the basin.

Wadi Sudr Basin	Peak (m ³ /s)	Time (min)	Volume of Flow (m ³)
Location (1)	396.39	930	9,375,477.30
Location (2)	401.17	915	9,322,995.60

**Figure 8.** Outlet hydrograph created by HEC-1 for the two proposed locations of dams.

Then a relation between the vertical heights and the corresponding horizontal distances to reach the lateral shape of the valley stream for each of the proposed sites was determined. The maximum height that the dam can reach was investigated to indicate the capability of construction. For the first location, the maximum permissible height of the dam is 61 m, and the maximum horizontal distance representing the width of the dam corresponding to this height is 520.37 m. However, for the second location, the maximum height is 36 m, and the maximum horizontal distance is 383.81 m, as shown in Figure 9. Accordingly, the shape of the side sector of the first location was more regular than the second one, which is better to facilitate the dam stability and reduce the construction cost.

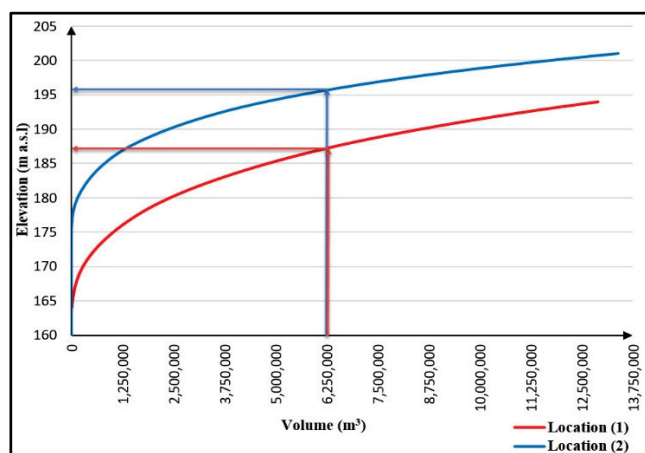
**Figure 9.** The cross-section in the selected locations of dams.

The dam storage capacity was calculated using the amount of precipitation, the area of the watershed, and the valley topography. Moreover, the annual rainfall volume was obtained. Furthermore, the volume of annual runoff was investigated using the volumetric runoff coefficient, which was estimated at 40% of the value of the volumetric flow, as shown in Table 7.

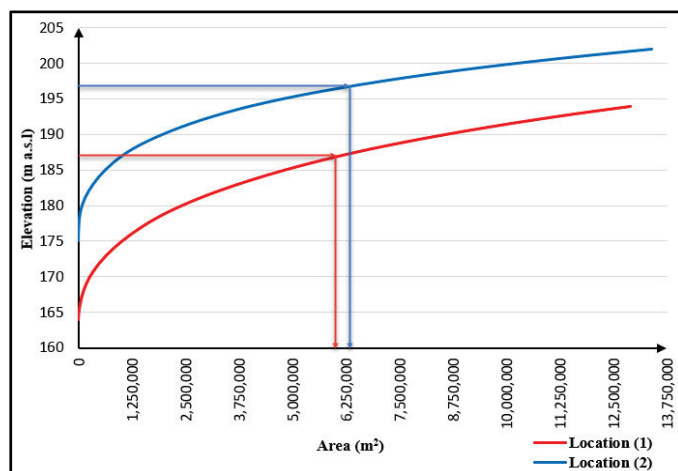
Table 7. The characteristics of the two dams.

	Location (1)	Location (2)
Precipitation	34.5 mm	34.5 mm
Area	455.53 km ²	452.97 km ²
Annual rainfall volume	15,715,785 m ³ (15.72 MCM)	15,627,465 m ³ (15.63 MCM)
Volumetric runoff coefficient	0.4	0.4
Runoff volume	6.286 MCM	6.251 MCM
The proposed height of the dam	23	22

The storage capacity was estimated for the two proposed locations of the dam from the storage elevation curve, as shown in Figure 10.

**Figure 10.** Relation between elevation and storage capacity for the two locations.

The expected height of the dam was investigated. This process was carried out for the two proposed locations for dams. It was found that the heights corresponding to the quantities of storage for the first and second proposals were 187 m and 197 m, respectively. Moreover, the heights of the first and second dam sites were 164 m and 175 m, respectively. Accordingly, the water height in front of the dam for the first location was 23 m, while it was 22 m for the second one. Figure 11 shows the relationship between the water storage height and the area of the valley upstream of the dam. For the first location, the water spread area was 6.081 million square meters, while the second was 6.587 million square meters.

**Figure 11.** Relation between elevation and area for the two locations.

Based on the analysis of the proposed locations of the two dams, it was found that the first location is more suitable for the construction of the dam for the following reasons: it has a higher storage capacity than the second, and the water depth in front of the dam is greater than in the second, the width of the valley is less than the second, and the area covered by water in the lake is less than in the second. In addition, the shape is, to some extent, more regular than the second, which is better for dam stability and reduces construction cost.

After settling on the first location of the dam in accordance with the above-mentioned criteria, Figure 12 shows a cross-section describing the water heights longitudinally, where they are 6 m and 8 m for right and left shoulders, respectively. Moreover, the highest water depth in the mid-span equals 23 m.

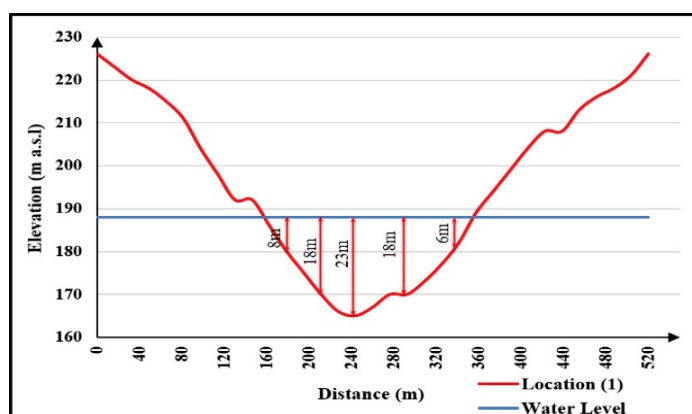


Figure 12. The height of the water longitudinally over the cross-section of the Wadi stream in the selected location of the dam.

4.4. Selection of the Most Appropriate Dam Location Using the Weighted Linear Combination (WLC) Analysis

In this stage, weighted linear combination (WLC) analysis and suitability index (SI) are used to select the most appropriate dam location for the two proposed locations. This is performed in two steps: identifying the standards for locating dams and reservoirs and using the weighted linear combination (WLC) analysis, and determining the suitability index (SI) that helps in the selection of the most appropriate location.

4.4.1. Identifying the Standards

The most pertinent criteria for locating dams and reservoirs were determined after a review of the literature. This exercise involved defining variables, restrictions, and exclusionary zones while taking into account the unique biophysical, socioeconomic, and data availability of the Wadi Sudr region, as shown in Table 8.

Weighted linear combination (WLC) is used in this work, which is based on an equal-weighted average and is simple to apply in a GIS setting using map algebra operations and cartographic modeling [42,43]. An appropriateness index was calculated by summing the products of the relative relevance, weight (% of influence), and standard suitability score of each criterion as follows:

$$SI = \sum w_i s_i \quad (1)$$

where SI is the suitability index, w_i corresponds to the relative importance of criterion i , and S_i is the standardized suitability score of criterion i .

Table 8. Criteria and rationale.

Criteria	Rationale
Elevation	Elevation influences the location of dams/reservoirs since it affects the water accumulation and movement. Lower elevations are preferable to higher elevations.
Slope	Higher slopes have a higher risk of landslides and put more pressure on the foundation of the infrastructures. The higher the slope in the construction site, the lower the potential for storing water and sediment, meaning that lower slopes have more storage volumes.
Soil type	Soil texture, structure, and depth influence the soil type, which determines soil infiltration rates and the amount of runoff.
Geological condition	Construction of dam affected mainly by the geological condition of the dam site; also, geology of underlying layer effect on the losses from dam reservoir.
Rainfall	Rain is the primary source of runoff and reservoir recharge. Rainfall intensity and its distribution are some of the pre-requisites for designing a water harvesting system.
Lineaments	Lineaments are linear features on the Earth's surface which reflect the geological structure, such as faults or fractures. Areas near lineaments are potential weakness zones for installing infrastructures.
Distance to village	The closer dams/reservoirs are to populations, the lower will be the costs of water transportation.
Distance to roads	The presence of roads and settlements close to the proposed sites will reduce the costs of water transportation.
Stream density	Provides the necessary runoff water for dam/reservoir function since different drainage network levels indicate different amounts of runoff water when the streams are upper stream tributaries, and main downstream streams, Areas with high drainage density ranked higher in suitability compared to areas of low drainage.
Land use/land cover	Areas proposed for constructing dams/reservoirs should be in or close to agricultural land to reduce the distances of farmers searching for water and the cost of transferring water from the reservoir to agricultural land. In addition, the primary objective of the dam/reservoir proposed for the study area is to assist crops field irrigation.
Dam height	The dam height affect directly on its cost and the dam safety; small dam ranked higher in suitability compared to the higher dam.
Dam length	The dam height width affect directly on its cost, long dam ranked less in suitability compared to the long dam.
Construction cost	The dam construction cost decreases the suitability of dam construction.

Table 9 shows the relative importance and its definition used in evaluating the signatories according to the criteria, and this evaluation is shown in Table 10.

Table 9. Relative importance, adapted from Saaty (1986) [44].

Intensity of Relative Importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one criterion over another
5	Strong importance	Experience and judgment strongly favor one criterion over another
7	Very strong or demonstrated importance	A criterion is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one criterion over another is of the highest possible order of affirmation
2, 4, 6, and 8	Intermediate	Can be used if necessary

Table 10. Site selection criteria used and level of suitability.

Criteria		Suitability Level				
		Highly Unsuitable	Not Suitable	Modestly Suitable	Suitable	Highly Suitable
1	Elevation (m)	530–870	320–530	170–320	50–170	0–50
2	Slope (m/m)	23.5–68.6	14.4–23.4	8.2–14.3	4.1–8.1	0–4
3	Soil	Gravel	Sand	Sandy silt	Silt	Clay
4	Geology	Pleistocene and Holocene sediments	Clastics with interbedded anhydrite and occasional limestone	Chalky limestone with flint bands and nodules at the base and thin successive chert bands on top	Gypsiferous yellowish green shale and gray to white intercalation with a thin flint band at the base	Sandy shales with phosphatic marl and limestone intercalations
5	Rainfall (mm)	0–10	10–25	25–35	35–50	50–70
6	Lineaments (m)	0–100	-	-	-	>100
7	Distance to village (km)	>54	35–54	23–35	1–23	0–1
8	Distance to roads (km)	40–50	28–40	16–28	1–16	0–1
9	Stream density	0–0.18	0.18–0.30	0.30–0.39	0.39–0.49	0.49–0.75
10	Land use/land cover	Evergreen forest, bare areas, artificial water bodies	Grassland, shrub lands, deciduous forest, thickets	Closed to open forest with shift cultivation, regularly flooded shrub lands	Open forest, aquatic/regularly flooded	The vegetation includes a variety of communities and species with wide tracts covered by plants
11	Dam height (m)	0–10	10–22.5	22.5–33	33–43	43–55
12	Dam length (m)	600–1000	450–600	190–450	75–190	0–75
13	Construction cost (M\$)	15.31–25.52	11.48–15.31	6.38–11.48	2.55–6.38	0–2.55

4.4.2. Suitability Index

Prior to doing the weighted linear combination (WLC) analysis, all the criteria were categorized into a similar evaluation scale (ESRI [45]). In this method, there were five categories of suitability used: highly unsuitable, not suitable, modestly suitable, suitable, and highly suitable. Dam sites should be placed at least 100 m away from lineaments since highly faulted areas are not suitable for building dams or reservoirs. The lineaments were divided into two suitability categories: highly inappropriate for distances under 100 m and highly suitable for distances above 100 m. In addition, classes of soil were categorized in accordance with how suitable they are [46]. The natural breaks (Jenks) classification method offered by ArcGIS was used to reclassify all of the remaining input criteria. This technique locates actual classes in the data, producing realistic depictions of data trends [47].

The level of suitability of the previous criteria was applied to each of the two proposed sites for the harvesting dams for the purpose of comparison between them, and then aggregated the criteria with equal weight using Equation (1) to obtain the value of the suitability index (SI) as shown in Table 11. From the previous results of the suitability index, it was concluded that the first location for the dam site had a value of 6.38, while the value of the second location was 5.46, and therefore the first site is the best according to the results of the weighted linear combination (WLC) analysis.

Table 11. Normalized level of suitability of the criteria.

Criteria		1	2	3	4	5	6	7	8	9	10	11	12	13	SI
Weight	Location 1	7	9	5	7	5	1	7	7	7	9	5	7	7	6.38
	Location 2	5	9	5	5	5	1	7	5	5	9	3	5	7	5.46

4.5. Design of the Dam in the Selected Site

For designing the proposed dam and finding its dimensions, such as crest width, dam height, and length, an empirical equation developed by Khattab (1991) [48] is used. Moreover, after studying the geometry of the studied valley, especially the proposed location for the dam construction, the dam's maximum height was selected to be 23 m. Furthermore, the other dimensions of the proposed dam are described in Table 12.

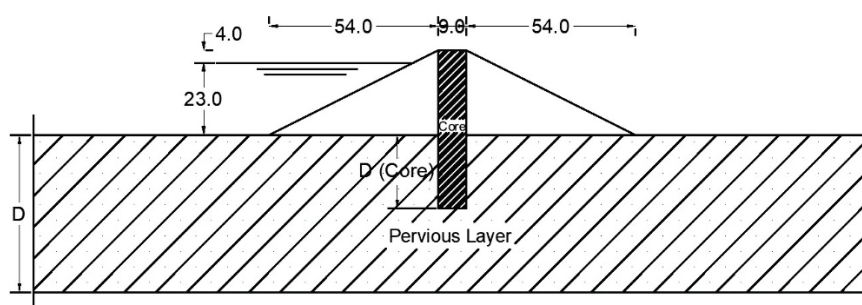
$$W = \frac{Z}{5} + 10 \quad (2)$$

where: W is the width of the crest, and Z is the height of the dam above the stream bed (that equals the height of the water and the freeboard).

Table 12. The proposed dam dimensions.

Parameters	Value
Crest width (b) m	9
Dam length (L) m	180
Dam height (H) m	27
Water height (h) m	23
U.S. and D.S. side slope (z:1)	2:1

Figure 13 describes the cross-section of the proposed earth dam. The seepage control method is chosen as an internal impervious core. The dam crest width is 9.0 m. Moreover, the upstream and downstream lengths are 54 m each, dam height is chosen to be 23 m, and a freeboard of 4 m is also selected. Furthermore, the impervious core penetration relative depth D_{core}/D , which significantly controls the quantity of seepage, depends on the soil properties of the foundation also the properties of the core. Many researchers described the relation between the core penetration and the seepage flow, as mentioned by Salem et al. [49]. In future work, we will deal in depth with modifying the design characteristics of the dam and making several different scenarios to keep the dam from collapsing, and choosing the most appropriate types. We will deal with detailed studies of the position of the core to reduce the rate of permeability of the dam.

**Figure 13.** Cross-section of the first proposal dam.

5. Conclusions

Flash flood risks should be evaluated, and protection measures should be provided to reduce its impacts. The present study aims to evaluate the geomorphological parameters at Wadi Sudr, South Sinai, Egypt. The present study combines geographic information system

(GIS) and watershed modeling system (WMS) to visualize and assess flood events in the study area. The morphological parameters, including linear, areal, and relief parameters, were determined for Wadi Sudr. Then constructing an earth dam for flood mitigation to protect the area from flash floods was discussed. GIS was used to analyze satellite images and determine the characteristics of the valley to reach the elongation and number of flow orders in the valley, and then WMS was used to estimate rainstorms and basin characteristics, as well as estimate the amount of rain that causes flooding. The data from GIS and WMS were used to select the best location of the protection dam based on some criteria, including storage capacity, water depth in front of the dam, width and shape of the valley, and the area covered by water in the lake. The morphometric analysis provided a quantitative portrayal of the Wadi Sudr watershed. It has 4029 streams connected with the seventh order of streams spread over an area of 547.45 km². Using GIS and WMS with the HEC-HMS program led to hydrological demonstration and flood hydrograph for the watershed. Two locations for protection dams were proposed to protect the area from flood hazards. A comparison between the two locations showed that the first option is more appropriate for the dam based on the selected criteria. The first location had a higher storage capacity (6.286 million cubic meters) than the second (6.251 million cubic meters). In addition, the water depth in front of the dam is greater than in the second, the width of the valley is less than the second, and the area covered by water in the lake (6.081 million square meters) is less than in the second (6.286 million square meters). The shape of the valley in the first option is more regular than in the second. Due to these reasons, the cost of constructing the dam in the first location will be less in addition to the dam stability will be higher. To further verify that the proposed location for the dam is the best, a comparison was made between the two locations according to 13 criteria using a weighted linear combination that depends on the equal weight, where the SI was found whose value was higher in the case of the first location than the second location. The proposed methodology is capable of protecting the study area from flood risks and harvesting large amounts of water that can be used for different purposes. It is also can be applied in different areas for flood risk evaluation and mitigation.

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Article

The Vital Roles of Parent Material in Driving Soil Substrates and Heavy Metals Availability in Arid Alkaline Regions: A Case Study from Egypt

Manal A. Alnaimy¹, Ahmed S. Elrys^{1,2,*}, Martina Zelenakova^{3,*}, Katarzyna Pietrucha-Urbanik^{3,4} and Abdel-Rahman M. Merwad¹

¹ Soil Science Department, Faculty of Agriculture, Zagazig University, Zagazig 44511, Egypt; dr_manalalnaimy@yahoo.com (M.A.A.)

² College of Tropical Crops, Hainan University, Haikou 570228, China

³ Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Kosice, 04200 Kosice, Slovakia; kpu@prz.edu.pl

⁴ Faculty of Civil, Environmental Engineering and Architecture, Rzeszow University of Technology, Al. Powstancow Warszawy 6, 35-959 Rzeszow, Poland

* Correspondence: aselrys@zu.edu.eg (A.S.E.); martina.zelenakova@tuke.sk (M.Z.)

Abstract: Despite studies focusing on soil substrates (carbon and nitrogen) and heavy metal availability, the impact of diversified parent materials in arid alkaline regions has received little attention. To reveal the influence of parent material, we investigated four different parent materials: fluvio-marine, Nile alluvial, lacustrine, and aeolian deposits. We assessed the effect of soil parent materials through selected soil physical and chemical properties, such as clay content, bulk density, pH, and available phosphorus (AP). The Tukey HSD test (SPSS ver. 23) was used to assess the soils derived from these different sediments. Using the R “glmulti” package, we examined this effect in a model of mixed-effects meta-regression. The sum of Akaike weights for models that contained each element was used to estimate the importance of each factor. The average contents of soil organic carbon (SOC) and total N in alluvial deposits were greater ($p < 0.001$) than those of marine, aeolian, and lacustrine deposits. A multivariate analysis in arid regions revealed that parent material, soil pH, and the availability of P had the greatest effects on SOC concentration, whereas clay content, available P, soil pH, parent material, and bulk density had the greatest effects on soil total nitrogen. The average content of Fe in the aeolian deposits was greater ($p < 0.001$) than those of marine, alluvial, and lacustrine deposits, without any significant differences between the latter two deposits. We found that the highest average contents of zinc (Zn), manganese (Mn), and copper (Cu) were recorded in alluvial deposits, with significant differences between other deposits. Soil parent material was the major factor impacting soil iron (Fe) content, along with clay content and soil pH. However, soil bulk density was the most important factor controlling soil Zn and Mn contents, while SOC drove Cu content. This study will help in developing a more accurate model of the dynamics of soil substrates and availability of heavy metals by considering readily available variables, such as parent materials, soil pH, soil bulk density, and clay content.

Keywords: SOC stocks; soil substrate availability; soil heavy metals; soil forming factors; soil genesis; alkaline soils

1. Introduction

Along with climate, biota, relief, and time, parent material is widely recognized as a significant soil-forming factor [1]. The variability of the mineralogical and physicochemical characteristics of soils reflects the parent material origin [2]. In agricultural, environmental, and geological investigations, parent material is used as a significant factor in soil classification and explaining soil units [3]. Under identical conditions of vegetation and

topography, various parent materials impact the chemistry and morphology of soils, particularly in arid and semiarid areas [4]. Parent material is frequently associated with critical soil physical properties (clay mineralogy, soil texture, soil structure, soil thickness, erodibility, and shrinkage and swelling potential) and chemical properties (cation exchange capacity (CEC), nutrient status, heavy metals, sodicity, salinity, and acidity) [5]. With the notable exceptions of oxygen, carbon (C), nitrogen (N), and hydrogen, which are taken predominantly from the atmosphere and organic matter, the majority of nutrients required for plant growth are derived primarily from parent material [5]. Soil organic C (SOC) and total N, known as soil substrate, are vital soil components for agricultural production, soil fertility, and, consequently, its quality [6,7]. Parent material type plays a primary role in soil C and N mineralization [8]. Moreover, variations in parent materials affect soil attributes, such as texture, soil bulk density, pH, and calcium carbonate (CaCO_3) [9]. On a global scale, numerous studies have identified that variations in soil substrate content have been correlated with vegetation type and climate [10]. Soil total N and SOC storage increased as the revegetation chronosequence progressed [11,12]. Various parent materials and soil texture influence bacterial diversity and nutrients, particularly SOC [13]. Heavy metals, such as manganese (Mn), zinc (Zn), iron (Fe), and copper (Cu), are fundamental for crop production, yield quantity, and holding yield responses to frequent NPK fertilizer [14]. However, an increase of these elements in soil beyond the permissible limit can reduce crop yields and be poisonous [15]. Soil parent material controls the original supply of those heavy metals from the weathering process and affects the balance between heavy metal retention and loss [16]. Exudates and organic acids produced by plants and microorganisms improve minerals weathering, and, ultimately, heavy metal release [17]. Heavy metals may be adsorbed to SOM and clay or interact with organic substances, thereby decreasing their mobility and speciation in soils [17]. These processes are influenced by soil formation, which alters the environment at various depths as soil horizons develop [16]. However, the impact of parent material on the original soil heavy metals supply in arid alkaline regions remains largely unknown [17].

The studied regions are situated in Egypt and have an important role in population, environmental, and agricultural development. These regions include a variety of parent material types, regionally derived from either alluvial, aeolian, marine, or lacustrine deposits. Aeolian sandy soils are those that develop on sand-based parent material as a result of wind action. In such soils, a sandy layer of ≥ 1 m is common, consisting primarily of fine sand with approximately 80% of particles falling between 0.25 and 0.05 mm in size [18]. Whatever the climatic circumstances, the prevalence of quartz in the bedrock makes it exceedingly unlikely that the suite of clay minerals present in the soil is the result of weathering [19]. The parent material of CaCO_3 -rich soil in the northwestern coastal region of Egypt is composed of a variety of rocks, e.g., limestone, sandstone, CaCO_3 -rich shale, or marl, formed as a result of weathering, translocation, and deposition processes under the arid climatic conditions [20,21]. The following parameters were used to choose the marine soil profiles: CaCO_3 , soil texture, electrical conductivity (EC), and hydrogen power; macronutrients such as nitrogen, phosphorus, potassium, and organic carbon; micronutrients such as manganese, zinc, iron, and copper; and other sodium and CEC [20]. High CaCO_3 content has an impact on soil pH, soil buffering capacity, CEC, base saturation, and nutrient availability, as well as the soil hydraulic conductivity and permeability [22]. Organic matter, clay content, soil texture, pH, Aluminum, Fe, and Calcium contents influenced P sorption [23]. Thus, poor P and K availability in plants results in issues that are more severe than their shortages. One of the key goals of plant nutrition is to increase the availability of these nutrients. The morphological features and particle size distribution show that the texture class is sandy loam and sand clay loam for the subsurface horizon [24]. Alluvial soils are among the most important and productive soil resources. The silt deposited by fluvial systems, such as streams and rivers, is alluvium, the parent material of alluvial soils [3]. Depending on the depositional environment and geologic materials source, alluvium can have a wide range of textures and compositions.

Alluvium can be found in all temperate zones and sits beneath geomorphic surfaces with ages ranging from zero to millions of years; it is therefore widely diverse [3].

Lacustrine deposits are sedimentary rock formations that developed at the bottom of ancient lakes [25]. Such deposits frequently have silt that was transported into the basin by a river or stream and frequently contain beds that are extensively laminated with silt, clay, and even carbonates. In geologic time, lakes are momentary; once the water stops flowing into them, they dry out and produce a formation [26]. In terms of Egypt, lacustrine deposits cover considerable areas, particularly in the northern parts near the lakes and the Mediterranean coastal zone, which are characterized by moist conditions that prevail most of the year [26]. Most of the profiles here have medium texture; the enrichment of lime or gypsum occurs in some profiles, and the soil color is characterized by a 10YR hue with a value between 3 and 5 and a chroma of mostly 2 [26]. Bluish or brownish mottling occurs in most of the profiles. The wetness is mostly associated with a high salinity due to the high groundwater table [27]. Furthermore, the solum of these soils is mostly shallow (45–100 cm) [28]. To our knowledge, our study is one of the first to elucidate the impact of contrasting parent materials on soil substrates and heavy metal availability in arid alkaline regions. Our study's objectives were to: (1) elucidate the patterns and controlling factors of soil substrates (SOC and total N) and heavy metals (Fe, Zn, Mn, and Cu) availability in arid alkaline regions under contrasting parent materials, and (2) compare soil metrics and features in various parent materials. Our study hypothesized that parent material would be the most important factor affecting soil substrates and heavy metal availability in arid alkaline regions.

2. Materials and Methods

2.1. Site Specification

Eight soil profiles were selected from four soil catchments of different parent materials in Egypt. These regions are situated in eastern, western, southern, and middle Egypt: Profile 1 (P1)—elevation 31 m a.s.l., $30^{\circ}48'56.008''$ N and $29^{\circ}23'38.764$ E; Profile 2 (P2)—elevation 26 m, $30^{\circ}53'5.766''$ N and $29^{\circ}43'2.444''$ E; Profile 3 (P3)—6 m, $30^{\circ}41'20.103''$ N and $31^{\circ}40'50.089''$ E; Profile 4 (P4)—14 m, $30^{\circ}23'24.156''$ N and $31^{\circ}10'1.891''$ E; Profile 5 (P5)—13 m, $30^{\circ}58'58.057''$ N and $31^{\circ}46'32.347''$ E; Profile 6 (P6)—2 m, $30^{\circ}53'5.766''$ N and $31^{\circ}49'57.703''$ E; Profile 7 (P7)—224 m, $29^{\circ}45'23.546''$ N and $30^{\circ}24'58.047''$ E; Profile 8 (P8)—56 m, $30^{\circ}14'2.767''$ N and $30^{\circ}14'7.755''$ E (Figure 1).

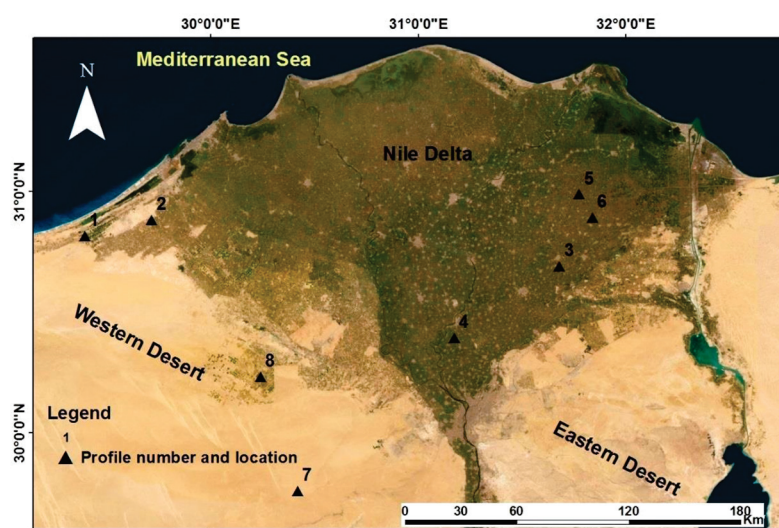


Figure 1. Location map of the soil profiles.

The soil survey was performed during the year 2021, and the pedons were dug according to soil morphological observations, to their depth, to the hard layer, or to the parent rock. The soil profile consists of a number of horizons, which were sampled in all 27

of the profiles. The representative soil samples were air-dried and sieved to 2 mm three times for chemical and physical analyses. According to the key of Soil Taxonomy [29], the field morphological description of these profiles and the main physical and chemical characteristics revealed that the soils were formed from fluvio-marine, Nile alluvial, lacustrine, and aeolian deposits. According to [30], the parent material of P1 and P2 was related to fluvio marine deposits, which consisted of sandy clay loam deposits and were produced by Pleistocene marine regressions. The parent material of P3 and P4 was related to alluvial deposits of silty clay sediments, while P5 and P6 were related to lacustrine deposits composed of clay sediments, and P7 and P8 were related to aeolian plains and inherited from shale, limestone, or sandstone as a parent material, which were composed of sandy sediments.

2.2. Soil Sampling and Laboratory Analysis

The international pipette method was used to perform the particle-size analysis [31]. The soil pH was determined by electrode immersion 1 h after stirring with a glass rod in a suspension of 1:2.5 soil:water. With intermittent agitation for one hour and centrifugation at 2000 rpm for 15 min, the EC of the soil was measured in a 1:1 soil-to-water ratio [32]. Soil CEC was estimated using the sodium acetate method [31]. The exchangeable sodium percentage (ESP, %) was computed as follows [33]:

$$\text{ESP} = (\text{Na}^+ / \text{CEC}) \times 100, \quad (1)$$

where Na^+ : measured exchangeable Na, cmol kg^{-1} ; CEC: cation exchange capacity, cmol kg^{-1} .

The following equation was used to determine the amount of coarse fraction in the soil (particles larger than 2 mm) [34]:

$$\text{Gravel content (\%)} = (\text{coarse materials weight} / \text{coarse and fine materials weight}) \times 100, \quad (2)$$

The SOC concentration was determined using the SOC pool calculation (SOCP). By multiplying the SOM by a factor of 0.58, the content of SOM for each horizon was first converted to a SOC percentage [34]. The SOC% was multiplied by the soil depth, soil bulk density (Mg m^{-3}), and soil fraction (<2 mm in size) to determine the SOCP (kg C m^{-2}) for each soil horizon [34]:

$$\text{SOCP} = [L \times \text{B.D} \times \text{SOC} \times (1 - F/100)] / 10, \quad (3)$$

where SOCP refers to the soil organic carbon pool for each soil horizon (kg m^{-2}), L is the thickness of soil horizon, SOC is the soil organic carbon content (wt%), F is equal to 10 mm for coarse soil fragment and 5 mm for fine soil fragment (wt%), and BD is the soil dry bulk density (Mg m^{-3}).

Available N was determined according to [35]. Available P was determined using the ascorbic acid method [35]. Ammonium acetate (1.0 N) was used to extract available potassium (K) at pH 7.0 and quantified by the flame photometer [35]. Total N in soil was digested by 10 mL H_2SO_4 + 5 mL HClO_4 and determined using the micro-Kjeldahl method [35]. Diethylene triamine penta-acetic acid (DTPA) was used to extract the available micronutrients from the soil samples (Zn, Fe, Cu, and Mn), which were then measured using an atomic absorption spectrometer [36].

2.3. Mineralogical Analysis

The original samples, which were derived from different deposits, were dried. Using bromoform, they were all set for mineral separation (Sp. Gr. 2.86 g cm^{-3}). Individual grains of heavy minerals were subjected to chemical analyses using a Phillips XL-30 environmental scanning electron microscope (ESEM), while semi-quantitative EDX was used for the mineralogical analysis of the mineral components [37].

2.4. Data Analyses

The comparisons between deposits were analyzed using the test of Tukey HSD (SPSS version 23). The “stats” package in R was used to analyze the correlation coefficients among the soil attributes. We used the variance inflation factor (VIF) to test the collinearities among factors and excluded factors with a VIF value greater than 10. We studied the soil parent materials’ impact and the soil’ physical (e.g., clay content and bulk density) and chemical (e.g., pH and available P) properties on the SOC, soil total N, and soil heavy metals (Fe, Zn, Mn, and Cu) content in a model of mixed-effects meta-regression using the “glmulti” package in R. The total of the Akaike weights for models that included a certain component was used to estimate the relevance of that factor, which can be viewed as the overall support for that factor across all models. The threshold was set at 0.8 to focus on the most crucial elements.

3. Results

3.1. Morphological Properties of Studied Soils

The surveyed soils were divided into four types: fluvio-marine, Nile alluvial, lacustrine, and aeolian deposits, based on soil classification, morphological description, and mineralogical, physical, and chemical properties. Diagnostic horizons descriptions and morphological aspects were identified using the criteria of [29] (Table 1). The soils of P1 and P2 were derived from marine deposits (limestone) with varying CaCO_3 levels, where the B_{ca} horizon developed as a result of CaCO_3 accumulation in the subsurface layer [38]. P3 and P4 were derived from the alluvium deposits, where the argillic B horizon developed. Salic and Natric B horizons developed in the soils of lacustrine deposits in profiles 5 and 6. Soils that originated from aeolian deposits (P7 and P8) were weakly developed and have no pedogenetic horizons. The solum thickness of the studied soil profiles varied from 60 cm in the soils originating from aeolian deposits to 2.0 m in alluvium soils. In dry conditions, the soil color ranged between very pale brown (10YR 7/3), dark grey (10YR 4/1), very dark greyish brown (10YR 5/2), and yellow (10YR 7/6) for marine, alluvium, lacustrine, and aeolian deposits, respectively. Clay content was the highest in alluvium- and lacustrine-originated soils, while the sand content was the highest in marine- and aeolian-derived soils (Figure 2). The uppermost surface of the marine deposit’s soils had a massive structure that was subangular and blocky downward. The structure was granular in the topsoil horizons of alluvial deposits, while it was subangular in the topsoil of lacustrine deposits and changed to massive profiles downward. The aeolian deposits were characterized by a weak structure along the profiles. In the coarse and fine textured horizons, respectively, the soil consistency ranged from non-sticky to moderately sticky and from non-plastic to moderately plastic (Table 1).

Table 1. Morphological description and mineralogy of the studied soil profiles.

Horizons	Depth, Topography, Munsell soil color (dry, moist), Soil texture, Soil structure, Stickiness (wet), Plasticity (wet), Soil consistency (moist), Soil consistency (dry); Calcium Carbonate, Clay and Sand Mineralogy *
	P1 (parent material: Fluvio-Marine); land cover (alfalfa plant)
A0	0–40 cm; flat; Dark grayish brown (10YR 4/1) dry; Dark gray (10YR 4/2) moist; SL; Ma; Sst; Spl; Lo; slightly hard dry; Moderately calcareous; quartz (+++), plagioclase (+), orthoclase (+).
B1	40–80 cm; Dark yellowish brown (10YR 3/6); Dark brown (10YR 3/2); SCL; Ma; Sst; Spl; Fi; slightly hard dry; Moderately calcareous; quartz (+++), plagioclase (+), orthoclase (+).
B2	80–120 cm; brown (10YR 5/3); Dark grayish brown (10YR 4/3); SCL; Sb; St; Pl; Vfi; hard dry; quartz (+++), plagioclase (+), orthoclase (+).
C	120–150; brown (10YR 5/3); Dark grayish brown (10YR 4/3); SCL; Sb; St; Pl; Vfi; very hard dry; quartz (+++), plagioclase (+), orthoclase (+).

Table 1. Cont.

Horizons	Depth, Topography, Munsell soil color (dry, moist), Soil texture, Soil structure, Stickiness (wet), Plasticity (wet), Soil consistency (moist), Soil consistency (dry); Calcium Carbonate, Clay and Sand Mineralogy *
P2 (parent material: Fluvio-Marine); land cover (wheat)	
At	0–30 cm; very pale brown (10YR 7/3) dry; yellowish brown (10YR 5/4) moist; L; Ma; Sst; Spl; Fi; slightly hard dry; extremely calcareous; quartz (+++), plagioclase (++), orthoclase (++)
B1	30–80 cm; light brown (7.5YR 6/4) dry; brown (10YR 5/6) moist; L; Sb; Vst; Vpl; Vfi; very hard dry; extremely calcareous; quartz (+++), plagioclase (++), orthoclase (++)
C	80–150 cm; Yellowish brown (10YR 5/6) dry; brownish yellow (10 YR 6/6) moist; L; Sb; Vst; Vpl; Vfi; extremely hard dry; extremely calcareous; quartz (+++), plagioclase (++), orthoclase (++)
P3 (parent material: Nile alluvial deposit); land cover (alfalfa plant)	
A0	0–60 cm; Almost flat; Gray (10YR 5/1) dry; dark gray (10 YR 4/2) moist; CL; Gr; Sst; Spl; Fi; slightly hard dry; Slightly calcareous; Montmorillonite (++++), kaolinite (++), mica (++), plagioclase (+), orthoclase (+), Microcline (+), quartz (+),
B1	60–100 cm; Dark gray (10YR 4/1); very dark gray (10 YR 3/1); CL; Sb; St; Pl; Fi; very hard dry; Montmorillonite (++++), quartz (++), kaolinite (+), plagioclase (+), orthoclase (+), Microcline (+)
B2	100–150 cm; Dark gray (10YR 4/1); very dark gray (10 YR 3/1); IC; Sb; St; Pl; Vfi; very hard dry; Montmorillonite (++++), quartz (++), plagioclase (+), Albite (+), orthoclase (+), Microcline (+)
C	150–200 cm; Dark gray (10 YR 4/1); very dark gray (10 YR 3/1); IC; Sb; Vst; Vpl; Vfi; extremely hard dry; Montmorillonite (++++), quartz (++), plagioclase (+), Albite (+), orthoclase (+), Microcline (+)
P4 (parent material: Nile alluvial deposit); land cover (vegetables)	
At	0–30 cm; Light gray (10YR 7/2) dry; Light brownish gray (10 YR 6/2) moist; SL; Gr; Sst; Spl; Lo; soft dry; Non calcareous; Montmorillonite (++++), quartz (+), kaolinite (+), plagioclase (+), orthoclase (+), Microcline (+)
B1	30–60 cm; SL; Sb; Sst; Spl; Fi; soft dry; Montmorillonite (++++), quartz (++), kaolinite (+), plagioclase (+), orthoclase (+), Microcline (+)
C	60–150 cm; SL; Sb; Sst; Spl; Fi; slightly hard dry; Montmorillonite (++++), quartz (++), kaolinite (+), plagioclase (+), orthoclase (+), Microcline (+)
P5 (parent material: Lacustrine); land cover (alfalfa plant)	
A1	0–20 cm; Almost flat; Grayish brown (10YR 5/2) dry; Dark gray (10 YR 4/1) moist; IC; Sb; St; Pl; Fi; hard dry; Moderately calcareous; Montmorillonite (++++), kaolinite (++), Vermiculite (+), illite (+), plagioclase (++), orthoclase (++), quartz (+)
A2	20–35 cm; grayish brown (10YR 5/2); Dark grayish brown (10 YR 4/2); IC; Sb; Vst; Vpl; Vfi; very hard dry; Montmorillonite (++++), plagioclase (++), orthoclase (++), kaolinite (+), Muscovite (+), quartz (+)
BC	35–85 cm; Dark clay (10YR 4/1); Very dark gray (10 YR 3/1); IC; Co; Vst; Vpl; Efi; very hard dry; Montmorillonite (++++), plagioclase (++), orthoclase (++), kaolinite (+), quartz (+)
C	85–135 cm; Dark clay (10YR 4/1); Very dark gray (10 YR 3/1); IC; Co; Vst; Vpl; Efi; extremely hard dry; Montmorillonite (++++), plagioclase (++), orthoclase (++), kaolinite (+), quartz (+)
P6 (parent material: Lacustrine); land cover (onion)	
A1	0–10 cm; Almost flat; Grayish brown (10YR 5/2) dry; Dark gray (10 YR 4/1) moist; IC; Sb; St; Pl; Fi; slightly hard dry; Moderately calcareous; Montmorillonite (+++), kaolinite (+), Vermiculite (+), illite (+), plagioclase (+), orthoclase (+), quartz (+)
A2	10–35 cm; grayish brown (10YR 5/2); Dark grayish brown (10 YR 4/2); IC; Sb; Vst; Vpl; Vfi; hard dry; Montmorillonite (++++), plagioclase (+), orthoclase (+), kaolinite (+), Muscovite (+), quartz (+)
BC	35–90 cm; Dark clay (10YR 4/1); Very dark gray (10 YR 3/1); IC; Ma; Vst; Vpl; Efi; very hard dry; Montmorillonite (++), plagioclase (+), orthoclase (+), kaolinite (+), quartz (+)
C	85–135 cm; Dark clay (10YR 4/1); Very dark gray (10 YR 3/1); IC; Ma; Vst; Vpl; Efi; extremely hard dry; Montmorillonite (++), plagioclase (+), orthoclase (+), kaolinite (+), quartz (+)

Table 1. Cont.

Horizons	Depth, Topography, Munsell soil color (dry, moist), Soil texture, Soil structure, Stickiness (wet), Plasticity (wet), Soil consistency (moist), Soil consistency (dry); Calcium Carbonate, Clay and Sand Mineralogy *
P7 (parent material: Aeolian); land cover (Non-cultivated)	
A	0–30 cm; Almost flat; Yellow (10YR 7/6) dry; Brownish yellow (10 YR 6/6) moist; S; We; Nst; Npl; Lo; loose dry; calcareous; quartz, opaques as; magnetite, ilmenite, leucoxene, hematite and the second is the non-opaques include zircon, garnet, monazite, rutile, silica (yellow and red silica) and green silicates (pyroxene and amphibole groups, epidote and mica group) (++++).
C	30–50 cm; Rock.
CD	50–100 cm; Hard rock
P8 (parent material: Aeolian); land cover (Non-cultivated)	
A	0–30 cm; Almost flat; Pale brown (10YR 6/3) dry; Very pale brown (10YR 7/3) moist; S; We; Nst; Npl; Lo; soft dry; Calcareous; quartz, opaques as; magnetite, ilmenite, leucoxene, hematite and the second is the non-opaques include zircon, garnet, monazite, rutile, silica (yellow and red silica) and green silicates (pyroxene and amphibole groups, epidote and mica group) (++++).
CD	30–60 cm; Hard rock.

Notes: * **Soil texture** according to [29]: SL: sandy loam; SCL: sandy clay loam; L: loam; CL: clay loam; LC: light clay; S: Sandy. **Soil structure**: We = Weak; Sb = Sub angular blocky; Co = Columnar; Ma = Massive; Gr= Granular. **Stickiness (wet)**: Vst = Very sticky; St = Sticky; Sst = Slightly sticky; Nst = non-sticky. **Plasticity (wet)**: Vpl = Very plastic; Pl = Plastic; Spl = Slightly plastic; Npl = non-plastic. **Soil Consistency (moist)**: Lo = loose; Fi = Firm; Vfi = very firm; Efi = Extremely firm. **Soil mineralogy**: + = few; ++ = common; +++ = many; ++++ = abundant.

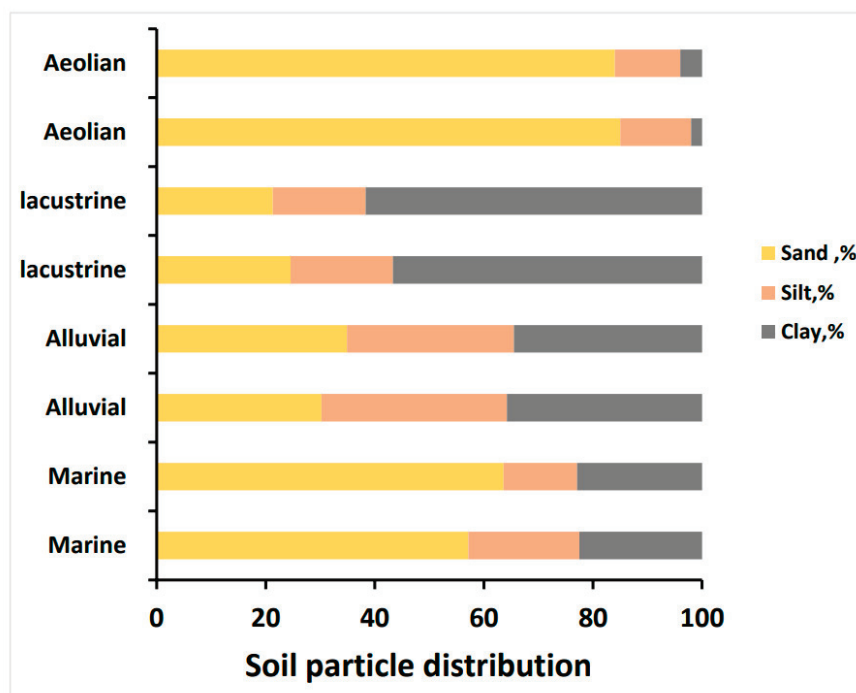


Figure 2. Soil texture of the studied sediments.

3.2. Soil Taxonomy of the Studied Pedons

According to [29], the soil classification was based on the presence or absence of diagnostic horizons, soil moisture, temperature regimes, morphological traits, and chemical and mineralogical composition. The soil temperature regime was hyperthermic, while the moisture regime was aridic. The studied soils were classified as aridisols, entisols, or vertisols based on soil taxonomy [29] (Table 2).

Table 2. Soil classification according to [29] of the studied soil profiles.

Profile	Order, Suborder, Great Group, Subgroup, Family
P1	Aridisols, Calcids, Petrocalcids, Typic Petrocalcids, Fine loamy, mixed, thermic
P2	Aridisols, Calcids, Petrocalcids, Natric Petrocalcids, Fine loamy, mixed, thermic
P3	Aridisols, Calcids, Haplocalcids, Typic Haplocalcid, mixed, thermic
P4	Aridisols, Calcids, Haplocalcids, Typic Haplocalcid, mixed, thermic
P5	Aridisols, Salids, Aquisalids, Typic Aquisalids
P6	Vertisols, Torrerts, Haplotorrerts, Sodic Haplotorrerts
P7	Entisols, Samments, Torripsamments, Lithic Torripsamments
P8	Entisols, Samments, Torripsamments, Lithic Torripsamments

3.3. Mineralogy of Sand and Clay Fractions

The sand and clay fractions are listed in Table 1. The sand fraction for all profiles showed that quartz predominated, with calcium-sodium feldspars (plagioclase) being the most common feldspar type. The aeolian and marine deposits had more quartz than the other types of deposits. Plagioclase, orthoclase, illite, kaolinite, quartz, and calcite formed the majority of the clay fraction in the marine deposits, with trace amounts of feldspar, dolomite, and iron oxides. On the other hand, alluvial deposits were formed of montmorillonite, kaolinite, mica, feldspars, and quartz. The lacustrine deposits were dominated by smectite, primarily in the form of montmorillonite, and kaolinite. The main constituents of the heavy fraction were opaque minerals, such as ilmenite, leucoxene, rutile, zircon, garnet, monazite, red silica, and green silicates (Table 3). Individual grains of heavy minerals were subjected to chemical studies utilizing a Phillips XL-30 Environmental Scanning Electron Microscope (ESEM) and semi-quantitative Energy Dispersive X-ray Analysis (EDX) to investigate the mineral composition (Figures 3 and 4).

Table 3. The content of total heavy minerals (g kg^{-1}) of the studied sediments.

Profile	Ilmenite	Leucoxene	Rutile	Zircon	Garnet	Monazite	Red Silica	Green Silicates
P1	3.222 ± 0.23	0.145 ± 0.03	0.250 ± 0.04	0.302 ± 0.06	0.155 ± 0.02	0.010 ± 0.00	0.616 ± 0.03	0.219 ± 0.04
P2	2.344 ± 0.31	0.205 ± 0.020	0.525 ± 0.07	0.306 ± 0.04	0.444 ± 0.02	0.030 ± 0.00	0.822 ± 0.06	0.323 ± 0.03
P3	0.064 ± 0.01	0.027 ± 0.00	0.017 ± 0.00	0.013 ± 0.00	0.027 ± 0.00	0.000 ± 0.00	0.245 ± 0.02	0.135 ± 0.01
P4	0.111 ± 0.00	0.062 ± 0.01	0.021 ± 0.00	0.003 ± 0.00	0.077 ± 0.01	0.011 ± 0.00	0.544 ± 0.06	0.212 ± 0.01
P5	0.053 ± 0.00	0.022 ± 0.00	0.011 ± 0.00	0.009 ± 0.00	0.025 ± 0.00	0.000 ± 0.00	0.237 ± 0.01	0.126 ± 0.02
P6	0.050 ± 0.00	0.024 ± 0.00	0.011 ± 0.00	0.009 ± 0.00	0.022 ± 0.00	0.000 ± 0.00	0.237 ± 0.01	0.124 ± 0.02
P7	3.930 ± 0.42	0.494 ± 0.05	0.740 ± 0.13	0.607 ± 0.04	0.543 ± 0.03	0.060 ± 0.01	0.943 ± 0.08	0.678 ± 0.05
P8	2.310 ± 0.22	0.159 ± 0.01	0.290 ± 0.06	0.212 ± 0.01	0.319 ± 0.04	0.000 ± 0.00	5.491 ± 0.35	0.794 ± 0.03

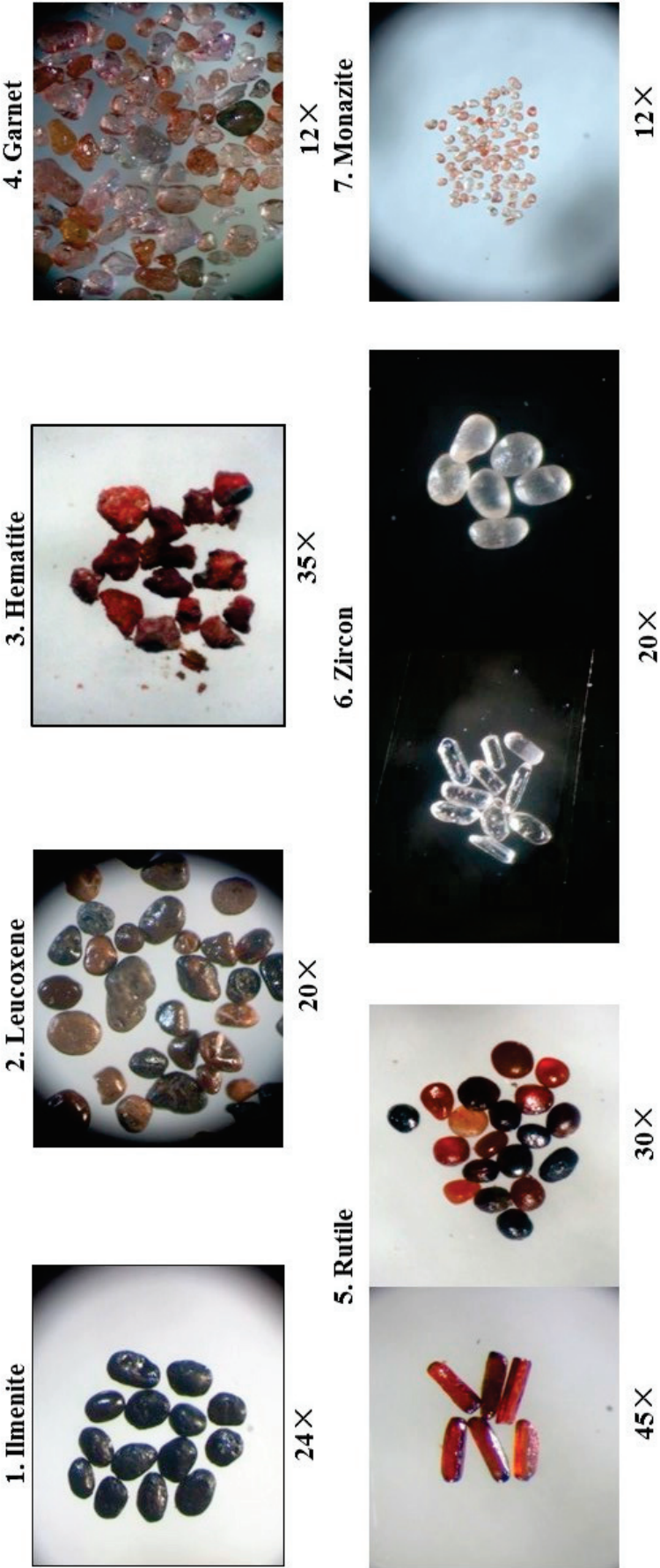
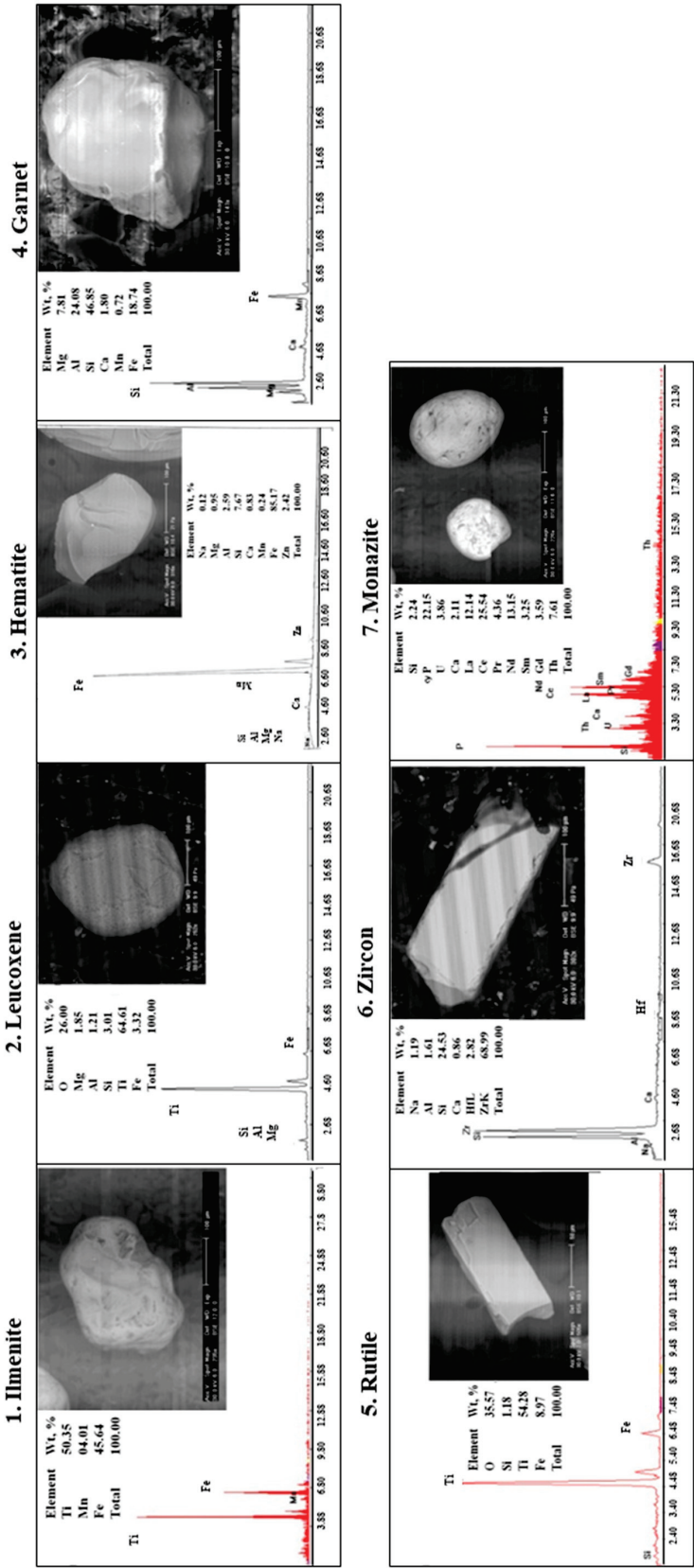


Figure 3. Photomicrograph showing the heavy minerals in the studied sediments.



3.4. Patterns and Controlling Factors of Soil Substrate Availability in Arid Regions

The soil physiochemical properties of the studied deposits are listed in Table 4. According to [36], the pH mean values in the studied soil profiles were from slightly to strongly alkaline. The soils ranged from being non-saline to very strongly saline, where lacustrine-originated soils had the greatest values. The studied soils ranged from being non-calcareous to extremely calcareous. The highest CaCO_3 levels were found in soils that were marine and aeolian in origin. Moreover, alluvial- and marine-derived soils had higher values of the CEC and available NPK content (g kg^{-1}) than the aeolian- and lacustrine-derived soils. Soil bulk density decreased in the alluvial- and lacustrine-derived soils and increased in the marine- and aeolian-derived soils. SOC and total N (mg kg^{-1}) also differed with deposits (Figure 5a), ranging from 0.74 to 5.50 and from 0.29 to 1.87, with an average of 2.90 ± 0.39 and 0.96 ± 0.12 , respectively. The average contents of SOC and total N in the alluvial deposits were greater ($p < 0.001$) than those of the marine, aeolian, and lacustrine deposits.

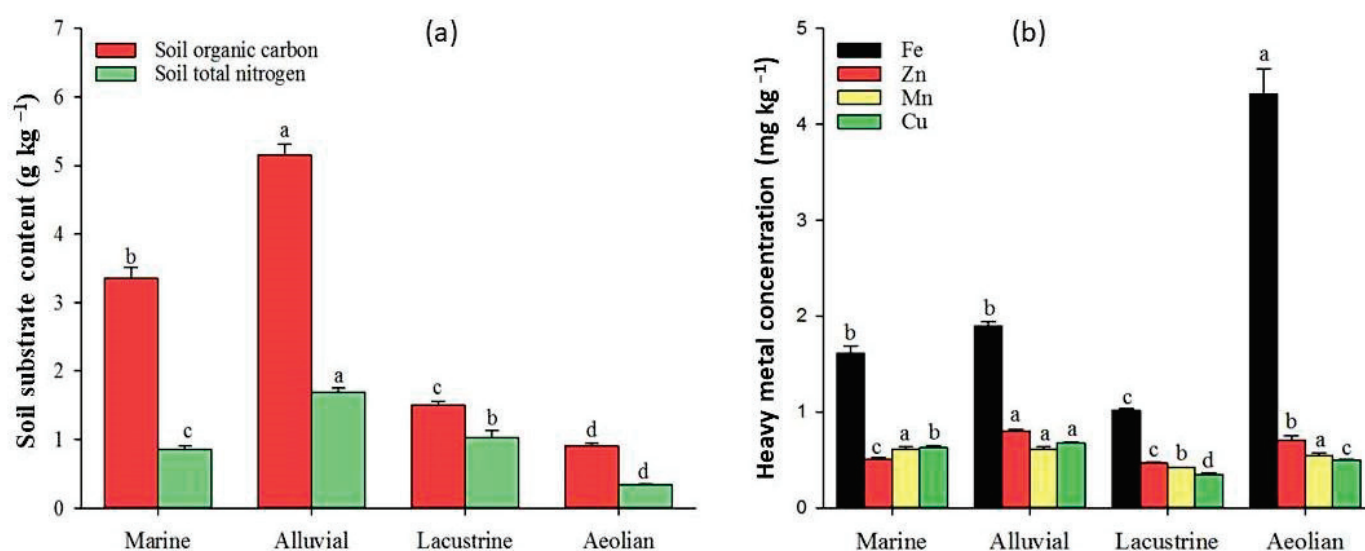


Figure 5. Effect of different parent material deposits (fluvio-marine, Nile alluvial, lacustrine, and aeolian) on (a) soil organic carbon (SOC) and soil total N content and (b) soil heavy metal (Fe, Zn, Mn, and Cu) content using variance analysis. Values are presented as means $\pm$ standard deviation (SD) using the number of the studied soil profiles ($n = 8$). For each attribute, bars with different superscript letters (a, b, c, and d) denote a significant difference between the effects of types of parent material at $p < 0.05$. The appearance of the same letter means that the difference was not significant.

The results of the multivariate analysis (Figure 6a) revealed that parent material, soil pH, and available P were the most important factors influencing SOC content in arid regions. Clay content, available P, soil pH, parent material, and bulk density were the key factors driving soil total N, but clay content was the most important one (Figure 6b). Based on Pearson's correlation (Table 5), SOC was negatively associated with soil bulk density ($p < 0.001$), EC ($p < 0.001$), ESP ($p < 0.01$), soil pH ($p < 0.01$), and soil Fe content ($p < 0.05$), but it was enhanced with increasing CEC ($p < 0.001$), available P ($p < 0.001$), available K ($p < 0.001$), available N ($p < 0.001$), total N ($p < 0.001$), C/N ratio ($p < 0.05$), soil Mn content ($p < 0.05$), and soil Cu content ($p < 0.001$). Soil total N content was negatively correlated with soil bulk density ($p < 0.001$), soil pH ($p < 0.05$), and soil Fe content ($p < 0.01$) and positively correlated with clay content ($p < 0.001$), CEC ($p < 0.001$), and available P ($p < 0.05$), available K ($p < 0.05$), available N ($p < 0.05$), SOC ($p < 0.001$), and soil Cu content ($p < 0.05$).

Table 4. The chemical properties of the studied sediments (Bulk density/Soil organic).

Profile	Bulk Density (g cm ⁻¹)	CEC (cmol _c kg ⁻¹)	CaCO ₃ (g kg ⁻¹)	EC (dS m ⁻¹)	pH	Available N (mg kg ⁻¹)	Available P (mg kg ⁻¹)	Available K (mg kg ⁻¹)	Total N (g kg ⁻¹)	Soil Organic C (g kg ⁻¹)
P1	1.67 ± 0.10	26.8 ± 1.27	336 ± 9.24	1.31 ± 0.06	8.40 ± 0.08	20.2 ± 0.44	12.2 ± 0.64	72.2 ± 1.85	0.87 ± 0.04	3.00 ± 0.02
P2	1.44 ± 0.15	24.2 ± 0.69	428 ± 6.81	3.35 ± 0.08	8.21 ± 0.00	16.8 ± 0.14	6.39 ± 0.18	67.1 ± 1.56	0.83 ± 0.10	3.70 ± 0.06
P3	1.30 ± 0.13	33.5 ± 1.10	4.90 ± 0.68	0.79 ± 0.12	7.83 ± 0.01	45.7 ± 1.79	19.8 ± 0.40	287 ± 7.16	1.67 ± 0.12	5.50 ± 0.08
P4	1.30 ± 0.13	32.1 ± 1.10	4.40 ± 0.87	0.77 ± 0.11	7.80 ± 0.01	43.2 ± 1.79	20.7 ± 0.40	298 ± 8.78	1.69 ± 0.09	4.80 ± 0.06
P5	1.38 ± 0.17	32.0 ± 1.04	36.7 ± 2.34	32.0 ± 2.34	8.50 ± 0.12	25.8 ± 0.64	6.70 ± 0.12	155 ± 4.16	1.02 ± 0.01	1.50 ± 0.06
P6	1.40 ± 0.17	31.0 ± 1.04	36.9 ± 2.34	29.0 ± 2.34	8.40 ± 0.12	23.8 ± 0.64	6.10 ± 0.12	150 ± 4.16	1.02 ± 0.01	1.40 ± 0.06
P7	1.80 ± 0.11	3.80 ± 0.27	820 ± 12.4	22.1 ± 1.73	8.07 ± 0.00	11.1 ± 0.28	4.60 ± 0.45	62.6 ± 1.56	0.34 ± 0.02	0.80 ± 0.03
P8	1.70 ± 0.16	3.97 ± 0.36	149 ± 5.20	8.90 ± 0.96	8.16 ± 0.02	10.3 ± 0.86	4.80 ± 0.52	60.9 ± 1.21	0.33 ± 0.02	1.00 ± 0.03

Table 5. Correlation coefficients between different soil properties for the studied sediments.

	Clay	BD	CEC	EC	ESP	pH	CaCO ₃	AP	AK	AN	TN	SOC	C/N	Fe	Zn	Mn
BD	***															
CEC	0.85 ***	−0.77 ***														
EC	0.27 ns	0.22 ns	−0.24 ns													
ESP	0.73 ***	−0.17 ns	0.32 ns	0.75 ***												
pH	0.23 ns	0.39 ns	−0.03 ns	0.52 *	0.71 ***											
CaCO ₃	−0.31 ns	0.31 ns	−0.11 ns	−0.32 ns	−0.14 ns	0.46 *										
AP	0.37 ns	−0.60 **	0.70 ***	−0.60 **	−0.31 ns	−0.61 **	−0.40 ns									
AK	0.56 **	−0.75 ***	0.69 ***	−0.28 ns	−0.07 ns	−0.62 **	−0.67 ***	0.89 ***								
AN	0.61 **	−0.77 ***	0.80 ***	−0.36 ns	−0.06 ns	−0.54 *	−0.54 *	0.93 ***	0.98 ***							
TN	0.65 **	−0.77 ***	0.87 ***	−0.40 ns	−0.02 ns	−0.46 *	−0.39 ns	0.92 ***	0.93 ***	0.98 ***						
SOC	0.35 ns	−0.70 ***	0.75 ***	−0.73 ***	−0.60 **	−0.56 **	−0.06 ns	0.88 ***	0.76 ***	0.84 ***	0.88 ***					
C/N	−0.33 ns	−0.004 ns	0.08 ns	−0.79 ***	−0.36 ns	−0.17 ns	0.71 ***	0.16 ns	−0.12 ns	−0.01 ns	0.10 ns	0.50 *				
Fe	−0.80 ***	0.67 ***	−0.89 ***	0.05 ns	−0.45 *	−0.18 ns	−0.12 ns	−0.40 ns	−0.39 ns	−0.52 *	−0.62 **	−0.54 *	−0.06 ns			
Zn	−0.28 ns	−0.022 ns	−0.12 ns	−0.24 ns	−0.62 **	−0.82 ***	−0.60 **	0.51 *	0.55 **	0.44 *	0.35 ns	0.32 ns	−0.04 ns	0.37 ns		
Mn	−0.33 ns	0.21 ns	0.11 ns	−0.63 **	−0.65 **	−0.34 ns	0.17 ns	0.49 *	0.17 ns	0.27 ns	0.29 ns	0.49 *	0.54 *	0.05 ns	0.44 *	
Cu	−0.18 ns	−0.25 ns	0.33 ns	−0.93 ***	−0.75 ***	−0.57 **	0.24 ns	0.67 ***	0.40 ns	0.49 *	0.53 *	0.83 ***	0.80 ***	−0.13 ns	0.41 ns	0.73 ***

Notes: BD, CEC, EC, ESP, AP, AK, AN, TN, SOC, and C/N refer to bulk density, cation exchange capacity, electric conductivity, exchangeable sodium percentage, available phosphorus, available potassium, available nitrogen, total nitrogen, soil organic carbon, and carbon-to-nitrogen ratio, respectively. * Correlation is significant at $p < 0.05$, ** Correlation is significant at $p < 0.01$, *** Correlation is significant at $p < 0.001$, ns refers to non-significant relationship.

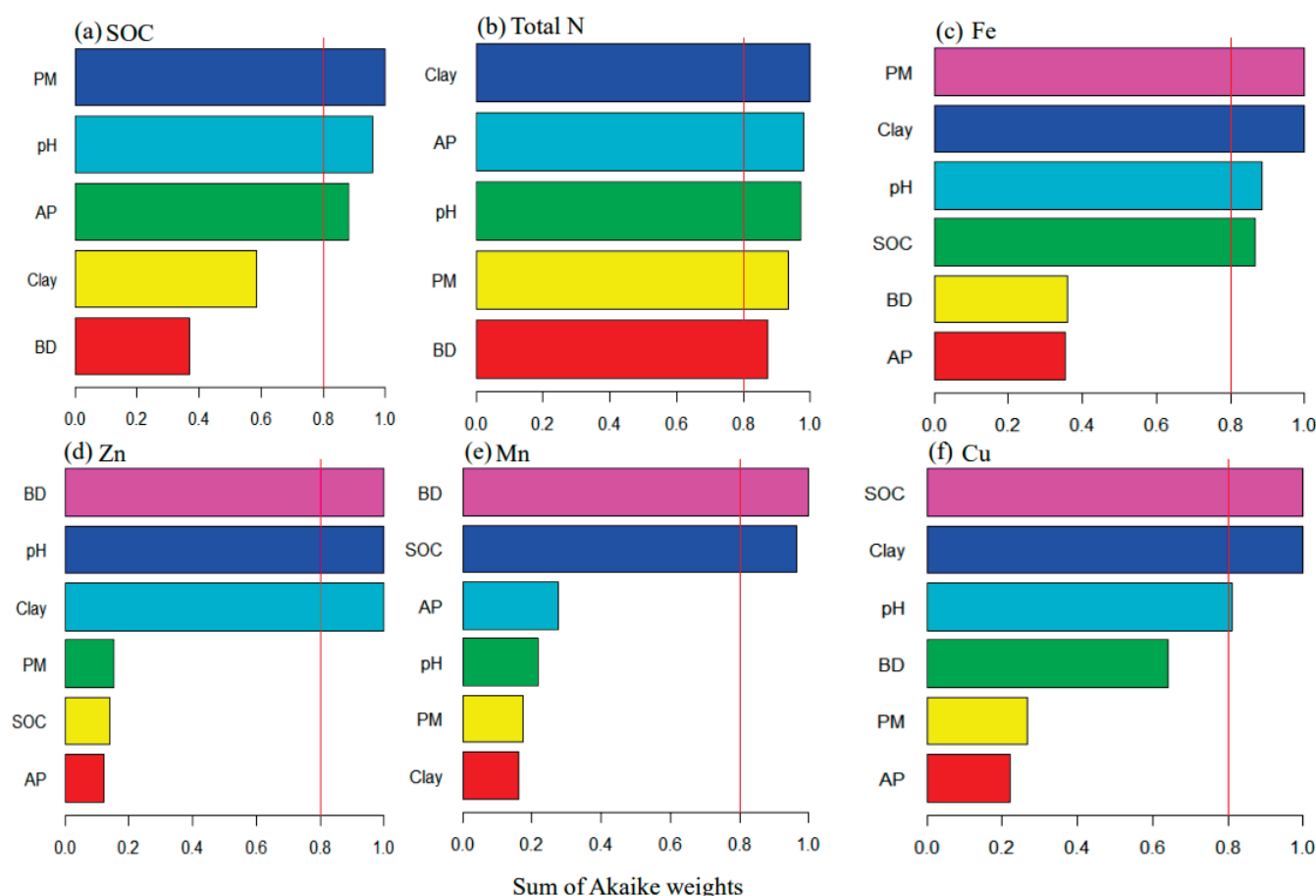


Figure 6. Model-averaged importance of the predictors of the impact of the factors on soil substrates and heavy metal content: (a) soil organic C; (b) total N stocks; (c) soil Fe content; (d) soil Zn content; (e) soil Mn content; (f) soil Cu content. The importance is based on the sum of Akaike weights derived from the model selection process using Akaike's information criterion corrected for small samples. The cut-off is set at 0.8 (red line) to differentiate between unimportant and important factors [39]. PM, parent materials; AP, available phosphorus; BD, soil bulk density; SOC, soil organic carbon.

3.5. Patterns and Controlling Factors of Heavy Metal Availability in Arid Regions

The soil content of heavy metals (mg kg^{-1}) varied, with deposits ranging from 0.99 to 5.17, from 0.44 to 0.86, from 0.41 to 0.72, and from 0.33 to 0.70, with an average of 2.38 ± 0.29 , 0.64 ± 0.03 , 0.56 ± 0.02 , and 0.57 ± 0.03 for Fe, Zn, MN, and Cu, respectively (Figure 5b). The average content of Fe in aeolian deposits was greater than those in marine, alluvial, and lacustrine deposits ($p < 0.001$), without any significant differences between alluvial and marine deposits. The highest average content of Zn, Mn, and Cu was recorded in alluvial deposits, with significant differences between other deposits (Figure 5b). Parent material, clay content, soil pH, and SOC were the primary impact factors on the amount of soil-available Fe (Figure 6c). Bulk density, soil pH, and clay content had the most effects on the amount of soil-accessible Zn, while parent material, SOC, and available P had little impact (Figure 6d). Only bulk density and SOC had an impact on the amount of soil-available Mn; the other parameters had no significance (Figure 6e). The major factors that determined soil availability of Cu were SOC, clay content, and soil pH, with little or no impact from bulk density, parent material, or available P (Figure 6f). Based on Pearson's correlation (Table 5), soil Fe content was negatively associated with clay content ($p < 0.001$), CEC ($p < 0.001$), ESP ($p < 0.05$), total available N ($p < 0.05$), soil total N ($p < 0.01$), and SOC ($p < 0.05$), but it increased ($p < 0.001$) with increasing soil bulk density. Soil Zn content was negatively correlated with ESP ($p < 0.01$), soil pH ($p < 0.001$), and CaCO_3 ($p < 0.001$), while it was positively correlated with available P ($p < 0.05$), available K ($p < 0.01$), and available

N ($p < 0.05$). Soil Mn content increased with increasing available P ($p < 0.05$), SOC ($p < 0.05$), C/N ratio ($p < 0.05$), and soil Zn content ($p < 0.05$), but it decreased with increasing EC ($p < 0.01$) and ESP ($p < 0.01$). Soil Cu content was negatively correlated with EC ($p < 0.001$), ESP ($p < 0.001$), and soil pH ($p < 0.001$) and positively correlated with available P ($p < 0.001$), available N ($p < 0.05$), and total N ($p < 0.05$), SOC ($p < 0.001$), C/N ratio ($p < 0.001$), and soil Mn content ($p < 0.001$).

4. Discussion

Parent material, time, climate, relief, and organisms are the five main variables that combine to form soil [40]. The sixth factor is human activity (anthropogenic activities), which influences soil formation [41]. These activities refer to a group of geomorphic and pedological processes, including irrigation, extensive ploughing, the burning of natural vegetation, and the production of genetically modified crops [42]. Each soil factor's proportional weight varies from place to place, but the totality of all factors frequently determines the type of soil that forms in any particular region [43]. Parent material, which might include organic materials or mineral rock, is the basis for the majority of soil formation processes [44]. Soil formation occurs when parent rock material is exposed to the atmosphere or when organic matter, minerals, or both are put on the Earth's surface [45]. Here, we offer four cases of some of the most significant effects of parent material influences on soil parameters [46]. Providing a straightforward quantification of all the soil components that affect soil formation is difficult in practice [43].

Parent material, which affects soil physical, chemical, and biological aspects, is one of the most important variables governing soil development and genesis [47]. It also supplies macro and micronutrients for plant growth as well as a habitat for soil microbes [47]. Thus, the ability of parent material to shape these qualities plays a significant role in the structure and communities of soil microorganisms [48]. The impact of parent material on the soil microbial population and structure is well understood [48]. However, there have been few investigations on the effects of parent materials on soil substrate (SOC and total N) and heavy metal (Fe, Zn, Mn, and Cu) availability [17,49]. Here, we discuss the impact of soil parent materials and soil physical (e.g., bulk density and clay content) and chemical (e.g., pH and available P) properties on SOC, soil total N, and soil heavy metal (Fe, Zn, Mn, and Cu) availability.

4.1. The Role of Parent Material in Controlling Soil Substrate Availability in Arid Regions

One of the purposes of this study was to assess the impact of soils derived from four different parent material categories (fluvio-marine, Nile alluvial, lacustrine, and aeolian) on soil substrate availability. SOC is gaining popularity, since it is the largest terrestrial carbon store and plays an important role in the global carbon cycle [50]. In the present study, SOC content was slightly higher in the soils developed from alluvial deposits compared to the soils formed from other deposits. The high content was most likely connected with continuous vegetation forms and dense cover [51]. The aggregation of soils from alluvial deposits enhances the stability of SOC contained within organo-mineral associations, resulting in increased resistance to soil erosion [52]. In addition, organic matter improves soil physical qualities, increases water infiltration, and improves soil structure. Thus, it appears that these sediments are ideal for a methodological case study to demonstrate how the lithological facies might change in response to river sedimentation dynamics. Manure application is a common source of SOM [52]. Furthermore, alluvial soils had higher CEC values than the other deposits, indicating their high clay and SOC content. The low SOC content in soils developed from lacustrine deposits can be attributed to long arid periods and poor vegetation [53]. One of the main issues with calcareous soils derived from marine deposits is a lack of organic matter. On the other hand, there are extensive areas of sandy soils that are being farmed, but the soil fertility is frequently low and depends on the SOC levels [54]. The pedons that were selected from aeolian deposits had the lowest SOC. Aeolian soils are typically characterized by having limited organic matter content,

a sandy or loamy sand texture, and very weak structural stability [55]. Because sand is inert and has minimal surface bonding on its particles, these soils also have relatively poor CEC [56]. Moreover, sand contains significant macropores, which are pores with a large particle size and typically contain air rather than water [56]. They are rather simple to manage without any compacting from mechanical cultivation [57]. Sandy soils are sensitive to slumping, mainly when there is a deficiency in organic matter [58]. More siliceous parent materials, such as illite and kaolinite, create clay minerals with a lower CEC than less siliceous parent materials, such as montmorillonite and vermiculite [59]; therefore, boosting the clay fraction's content could benefit SOC stocks in two different ways, thus playing a relatively greater role in the CEC [60]. Moreover, the predominance of quartz for soils inherent from aeolian and marine deposits would facilitate leaching due to its low surface area and charges [61]. Parent material has an impact on the nutrients in the soil [62], which may then change how much root exudation occurs and how the rooting system develops. In the present study, the low available NPK level of aeolian deposits was due to the low organic matter and clay content. In addition, nutrients generally increase as the parent material becomes less siliceous. Owing to low nutrient retention, additional supplies of fertilizers are used to keep nutrient levels at their ideal levels [61,63]. Liming is important, but it should only be performed little and often. Because it serves to store water and plant nutrients in the soil and to enhance soil structure and biological activity, organic matter, especially as humus, is very advantageous [64]. Many different crops can be grown successfully in sandy soils, including carrot, beetroot, cucumber, muskmelon, watermelon, fenugreek, radish, etc. [65]. However, alluvial deposits had the highest available NPK content as a result of their high content of clay and organic matter, cultivation management processes, and vegetation; consequently, the majority of the biological activities occurred there [66]. Soil microbial biomass, soil substrate availability, and soil bulk density drive soil gross N mineralization [67,68]. Soil substrate availability is a main factor controlling soil dissimilatory nitrate reduction to ammonium. In addition, clay minerals in the old alluvial plain were generated by subsequent Nile floods from Pleistocene deposits [69]. We found that montmorillonite, vermiculite, and illite are the clay minerals identified in alluvial soils, in decreasing order of abundance [70]. They have the capacity to store irrigation water and adsorb more exchangeable cations in aqueous media, providing plant nutrients [70]. In the current study, parent materials affected soil chemical aspects; thus, soils formed from lacustrine and marine deposits had the highest pH values, which were attributed to shell fragments, the accumulation of CaCO_3 , and a high value of ESP [23]. In addition, these soils were classified as saline soils due to the great quantities of soluble salts in Lake Manzala [71,72]. It is essential to cultivate such soils with crops suitable for the local climate, topography, and water availability, which includes halophyte plants, as well as growing crops with high economic yields that can resist salt [73]. Soil conditioners may be used to improve the chemical and physical properties of such soils [74]. On the other hand, soils representing alluvial River Nile sediments (the old deltaic plain) had the lowest values of soil pH, EC, CaCO_3 , and ESP, as well as advanced cultivation processes, for a long time [7]. Rice, corn, cotton, wheat, oranges, and potatoes are the most common crops grown in these soils [75]. The northern Mediterranean zone's arid or semiarid soils are primarily calcareous [76]. The amount of CaCO_3 in the soil is an accurate indicator of how the marine parent material has affected the soil [76]. The limestone and calcarenite ridges that eroded into the surface layer of Egypt's northern coastline resulted in the majority of the sand being formed by the combination of CaCO_3 [77]. As a result of the exceptionally low acidity of carbonic acid, calcareous soils are often alkaline in character [78]. They may contain a calcic horizon, a layer of secondary carbonate deposits (typically calcium or magnesium), more carbonate than an underlying layer by at least 5%, and more carbonate than the horizon, so they are identified by the parent material's CaCO_3 content [78]. Acid-forming fertilizers, such as ammonium sulphate and urea fertilizers, sulfur compounds, organic manures, and green manures, are considered effective ways of reducing the pH of soil to a neutral value [20]. Wheat, alfalfa, sunflower, barley, date palm, cotton, and olive were the

optimum crops for land use in this unit [79]. In aeolian soils, carbonates and soluble salts may be carried by the wind; nevertheless, their endurance in the soil is caused by limited leaching [80]. Poor drainage and the use of saline water for irrigating agricultural crops is reflected in the high salinity of these soils [81].

4.2. Drivers of Heavy Metal Availability in Arid Regions

Understanding the variables affecting the distribution of heavy metals in agricultural soil is crucial [82]. A number of factors, including intrinsic soil properties (such as pH and soil P content), environmental conditions (such as climate and topographic moisture), land use characteristics, and soil type, can influence the availability and mobility of heavy metals in the soil [83]. Moreover, soil heavy metal levels decrease with increasing distance from the source due to topography and water flow [84]. The most critical factor among them is soil pH, since it regulates nearly all physical, chemical, and biological processes in soil that affect metal availability, such as metal solid phase dissolution and the precipitation, complexation, and acid–base interactions of metal species [85]. The rivalry between free metal ions and other cations in solution increases when pH decreases metal ion sorption on soil particles, leading to increased metal concentrations in the soil solution [86]. Alkaline soils require particular management strategies, such as the addition of acidifying minerals, organic matter, and gypsum, to raise pH levels [87]. Growing legumes can help maintain a lower pH. Using alkalinity-tolerant crops and pastures can also help mitigate the effects of high pH levels [88]. This conclusion suggests that when developing models to predict soil heavy metals in response to parent materials and soil pH, these factors should be taken into account. In our study, the SOM content had a significant impact on the heavy metal availability in the soil because it adsorbs metals through complexation processes [89]. In addition, the availability of heavy metals was found to be highly correlated with EC, where higher EC values are typically associated with greater metal release rates [90]. The amount of heavy metals in their soluble forms, such as Ni, Cu, Zn, and Pb, is often increased in soil that has been fertilized with NPK and manure.

5. Conclusions

Eight soil profiles derived from four different parent materials—fluvio-marine, Nile alluvial, lacustrine, and aeolian deposits—were meticulously set out in the current study so that their effects on soil substrate and heavy metal availability could be assessed. The soil parent material clearly differed in the contents of SOC and total N through its impact on the soil chemical and physical properties, mainly clay content. The major factor that determined soil Fe availability was the soil parent material type, whereas soil bulk density was the driver of soil Zn and Mn contents. Clay content was the most important factor affecting soil Cu content. The findings of this study could deepen our understanding of the effect of soil parent materials on soil substrates (SOC and total N), which are the main factors controlling soil nutrients availability, and could also deepen our understanding of micronutrient management in alkaline soils. This study is useful for agricultural authorities to help farmers understand their soil and how to manage it. Both anthropogenic activities and agricultural land use should be considered when assessing the impact of parent material change on different soil aspects.

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Article

Effect of Changing the Shape and Size of Inlet Area of Grates on the Hydraulic Efficiency of Urban Rainstorm Drainage Systems

Ismail Fathy ¹, Gamal M. Abdel-Aal ¹, Maha Rashad Fahmy ¹, Amira Fathy ², Martina Zelenáková ^{3,*}, Hany F. Abd-Elhamid ^{1,4} and Mohamed A. Nassar ¹

¹ Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt

² Ministry of Water Resources and Irrigation, Sharkia 44519, Egypt

³ Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Kosice, 042 00 Kosice, Slovakia

⁴ Center for Research and Innovation in Construction, Faculty of Civil Engineering, Technical University of Kosice, 042 00 Kosice, Slovakia

* Correspondence: martina.zelenakova@tuke.sk

Abstract: Urban rainstorm drainage systems are used to collect the surface runoff from streets and other land surfaces through grate or curb openings that convey it to the drains. The quantity of surface runoff that is not discharged to the urban rainstorm drainage systems due to inadequate grate size or because the grate capacity is exceeded can cause flooding, immoderate hazards to drivers and pedestrians, and disrupt urban activities. This study aims to carry out experimental work to investigate the hydraulic efficiency of urban rainstorm drainage systems using different types of grates (shape and size of inlet area) for harvesting excess rainwater. Different grate shapes (five) with different inlet areas were investigated, as well as using three relative grate inlet areas (26%, 51%, and 64%). The results of the experimental work indicated that the best grate shape is the grate type 4 which provided the smallest reduction in discharge efficiency within 8.7%. The results specified that changing the size of the inlet area of grates from (26%) to (64%) has a significant impact on urban rainstorm drainage systems efficiency which decreased by 4%. In addition, the dimensional analysis principle with multi regression analysis were used to develop an empirical equation to compute the efficiency of urban rainstorm drainage systems. The relation between grate shapes and the relative inlet area with the efficiency of grate capture provides an indication to the decisionmakers to increase the time period for maintenance which will save the cost for further maintenance. The presented empirical equation can help decisionmakers for monitoring the current situation of grate blockage (relative grate inlet areas) and the corresponding efficiency. This study is beneficial for future road drainage system construction to avoid problems by assessing the performances of the current drainage systems and proposing mitigation measures to avoid improper functioning. Finally, this methodology can help to improve the efficiency of urban rainstorm drainage systems that can reduce the risks of urban floods.

Keywords: urban flood; rainstorm drainage systems; grate shape; inlet area; hydraulic efficiency

1. Introduction

Urban rainstorm drainage systems have become an important issue in the planning and management of urban drainage in different countries. Adequate knowledge of the hydraulic behavior of surface drainage structures requires the consideration of surface flow hydraulic, grate capacity, and hazards related to urban runoff during the storms. These factors affect the design of a surface drainage system. The hydraulic behavior of grate inlets has an impact on the efficiency of urban rainstorm drainage networks. Asfaw [1] investigated that the stormwater drainage system was inadequate to convey the peak discharge for the required design period, in which the drainage system filled with sediment

and rubbish material. The results for those problems were due to the drainage system design, the hydraulic analysis, and type of drainage system provided. Several studies have used the dimensional analysis technique to obtain empirical equations that correlate the studied parameters in a certain place [2,3].

The American Association of State Highway and Transportation Officials (AASHTO) [4] investigated that the transverse slope of a road can vary from -0.10 to $+0.10$. When the side slope is more than zero, the flow collected above the grate has the characteristics of a triangular flow channel. In contrast, parking lots and pavements are the zones where only longitudinal gradient is realized. Magdi [5] used two case studies to investigate the effects of a deficient drainage system on road performance in Khartoum, Sudan. The causes of road failure in the first 5 years following construction were identified. In this study, it was found that there are four main causes for the early deterioration of road pavements including poor maintenance structures, poor drainage system design and construction, lack of local standards of practice, and the use of low-quality materials. Singh et al. [6] found that good road drainage is essential to reducing the environmental impact of roadways. Moreover, they found that removing surface water quickly led to enhanced road safety, minimized traffic interruption, and extended the lifetime of the road surface and related infrastructures as much as possible.

Owuama et al. [7] examined options for a road network's sustainable drainage system, such as a trenchless drains, which include an absorption unit and grass cover. It was discovered that the technology would offer a low-cost, aesthetically pleasing, and practical method for removing road surface runoff with little inconvenience to users and little harm to the environment. It was determined that trenchless drains easily dispose the stored surface water and add aesthetic appeal to the surrounding. Izzard [8] indicated that the flow above the inlet lip is crucial (the inlet is acting as a weir), and the water depth declines linearly throughout the inlet length. The total flow per length of the inlet was calculated for the whole inlet length to obtain the flow discharge into the inlet. Mostkow [9] showed that the efficiency increases as longitudinal slope decrease to horizontal slope. This concept is useable only if grate bars are parallel to the flow path. However, in actual cases plane grades may make blockage problems and rubbish accumulation.

The hydraulics of grate inlets with several coefficients via Reynolds number and Froude number were studied by Mustafa [10]. Diverse shapes of grate inlets located in channels and reservoirs were utilized and an orifice-oriented inlet was used for multiple orifices, single orifice, and orifices with a certain amount of roughness on the adjacent bed. The results presented differences in the discharge coefficients that are suitable to the calculation of the actual flow entering the inlet for several flow conditions. Gahin [11] analyzed data from the Federal Highway Administration's (FHWA) experiments to establish the sort of drainage inlet that is most effective. Six distinct grate types with differing bar arrangements and longitudinal slopes were tested in these experiments. These experiments presented two dimensionless parameters for each type of grates. According to the study, transverse bar grates performed hydraulically worse than grates with parallel bars to the flow direction.

Michael et al. [12] examined combining techniques for enhancing the performance of hydraulic models for urban rainfall drainage systems utilizing simple black-box models. HYDROWORKS software was used to implement this technique in a storm system in a small catchment. Four black-box models were tested as an updating procedure to improve the output of the hydraulic model for real-time forecasting. Updated forecasts were studied for a range of lead times and the overall model efficiencies were compared. The approach can provide enhanced information for the operational and real-time control of storm water drainage systems. The system is valuable for small urban catchments and for catchments with steep slopes with short catchment response times.

A number of studies have been conducted for determining stormwater drainage efficiency. Carvalho et al. [13] used a two-dimensional (volume of fluid/fractional area volume obstacle demonstration) model to define stormwater drainage efficiency. Rainfalls

of various intensities were simulated by a network of pipes projected 1.0 m above the road surface with sprinklers at 2.0 m staggered intervals. Lopes et al. [14] developed a three-dimensional method using the OpenFOAM program to study the surcharge of the jet characterization, flow in a gully storm system, and its height above the gully. The detailed mesh allowed the investigators to obtain respectable similarity between experimental and numerical results. Sezenöz [15] analyzed the grates' efficiency using the Flow 3D program. The used platform was built from fiberglass with a height of 10 cm and a width of 90 cm. A single grate system and single longitudinal slope of 1% was carried out in the experimental study. The results indicated that the efficiency rates with total flow showed a bell-shaped curve; this means that by increasing flow rates, the efficiency of the grate increases until it reaches the peak point, then starts to decrease. Total discharge, longitudinal slope, shape, and width of the channel affected the intercepted flow rate and efficiency of the grate. For higher discharges, it can be highlighted that efficiencies are extremely reduced and become inefficient.

The hydraulic efficiency of continuous transverse grates, despite the importance and the general use of this type of surface drainage structure was investigated by Manuel [16]. A flume with dimensions of 5.5 m long and 1.5 m wide with a platform able to simulate road lanes with longitudinal slopes up to 10% and side slopes up to 4% was used. By available system capacity, it is possible to test inlet grates and examine their hydraulic capacity for a significant range of flows (0–200 L/s). Linear equations were developed by linking the Froude number with hydraulic efficiency. These findings have been updated and enhanced by new information acquired from new experimental trials. These equations established a connection between certain parameters relating to the geometry of the grate and the flow rate per unit width upstream of the grate and the hydraulic efficiency. Wakif and Sabtu [17] improved the knowledge and effect on the hydraulic properties of gully grates caused by vertical depression. They attempted to develop empirical equations that describe the relationship of significant parameters, such as Froude number and hydraulic efficiency. A full-scale physical model was created to simulate the actual condition on site. Experimental results indicated that vertical depression decreases the hydraulic efficiency by 6% to 10% for a 20 mm depressed single grate.

Experimental studies have been used to determine the discharge coefficients through an inlet for surcharged pipe conditions. Cosco et al. [18] defined the discharge coefficients using actual scale experiments to deliver information for inlet manufacturers and practitioners. Longitudinal and transversal gradients varied between (0–10%) and (0–4%), respectively, whereas the tested discharge values ranged between (25–200 L/s). In order to calculate the discharge coefficients if the flow completely covers the grates, the inlets of three grates were examined. A relationship between discharge coefficient and upstream Froude number was demonstrated for supercritical flow conditions. Regarding the orifice method, the discharge values for the Barcelona, Meridiana, and E-25 grated inlets varied between (0.055–0.294), (0.033–0.431), and (0.054–0.423), respectively. In contrast, the coefficients for the weir assumption ranged between (0.009–0.244), (0.003–0.245), and (0.006–0.286), respectively. Gómez et al. [19] presented an experimental method to compute discharge coefficients through an inlet for overflow pipe circumstances. Tests were run using a real laboratory platform that simulated a road lane. Different surcharged inlet flows ranging from 10 to 50 L/s were taken into consideration. For surcharged flows of 10 to 50 L/s, the obtained discharge coefficient ranged between 0.13 and 0.41. According to the results of the sensitivity analysis, discharge coefficients can be regarded as constant for any roadway longitudinal slope.

The efficiency of grates under different conditions have been studied either experimentally or numerically. Guo et al. [20] inspected experimentally eight types of such grates used in China. A full-scale physical model simulating a 3.0 m wide, and 12.0 m length road was built for 320 hydraulic experiments with different inlet flow rates and road longitudinal grades. The grates' hydraulic efficiencies under diverse settings were estimated, and the influencing factors were studied, including the grates' geometry (grate

length, effective width, effective length, effective width ratio, effective length ratio opening style, and opening rate) and Froude number. To correlate the hydraulic efficiency and affecting factors, empirical equations were provided. The presented results are helpful for understanding continuous transverse grates and enhancing the grates' engineering design. Aranda et al. [21] used an Iber model to present a method based on the assessment of grate inlet efficiency and hydraulic numerical simulation. The method is appropriate for application to design criteria regarding the standards of various countries. Through complete control of the hydraulic behavior of each of the grate inlets considered in each scenario, the proposed method makes it easier to conduct sensitivity evaluations of the performance of various scupper arrangements. To improve decisions and find solutions that maximize efficiency, several solution comparisons can be made using the comprehensive hydraulic information.

According to the above lecturer review, there no study has been performed on linking both the shape of grates and the inlet areas of grates with the efficiency of urban rainstorm drainage systems, which certainly affects the design, operation, maintenance, and the cost of the system. Moreover, the decisionmakers actions for the maintenance of the network is related to the blocked area of the grates (percent of grate inlet area) along the drainage system, which also affects the operation and cost of maintenance. Therefore, this study aims to conduct an experimental work to determine the hydraulic efficiency of using different grate shapes and varying inlet area with different storm events. Moreover, to develop an empirical equation to correlate the efficiency of urban rainstorm drainage systems with grate shapes and the inlet area of grates. The relation between grate inlet area and efficiency of grate capture provides an indication to the decisionmakers to increase the time period for maintenance, which reduces the cost of maintenance and operation. The developed empirical equation can provide an indicator that can help decisionmakers to take action by investigating the current situation of grate blockage (relative grate inlet areas) and corresponding efficiency.

2. Dimensional Analysis

The discharge efficiency of urban rainstorm drainage systems depends on a number of parameters such as total discharge, the relative grate length, the relative grate width, the relative grate height, and the relative inlet area. A dimensional analysis based on THE Buckingham theory [22] was used to develop a relationship between the discharge efficiency and the other parameters involved in the phenomenon which are shown in Figures 1 and 2. Applying the Buckingham theory, the functional relationships of the discharge efficiency may be expressed as the following:

$$\mathcal{E} = f(Q, L_o, W_o, H_g, A_g) \quad (1)$$

where $\mathcal{E}$ is the efficiency of discharge (q_i/Q), Q is the total discharge, q_i is the intercepted discharge, L_o is the relative grate length (L_g/L), L_g is the length from beginning of flume to the grate position, L is the length of the flume, W_o is the relative grate width (W_g/W), W is the channel width, W_g is the water spread beside every grate, H_g is the relative grate height (h_g/h_u), h_g is the water depth at grate upstream, h_u is the water depth at flume upstream, A_g is the relative grate area (a_o/a_g), a_o is the grate inlet area, a_g is the grate area, g_1, g_3, g_5 refers to the grate's position, and h_d is the water depth at flume downstream.

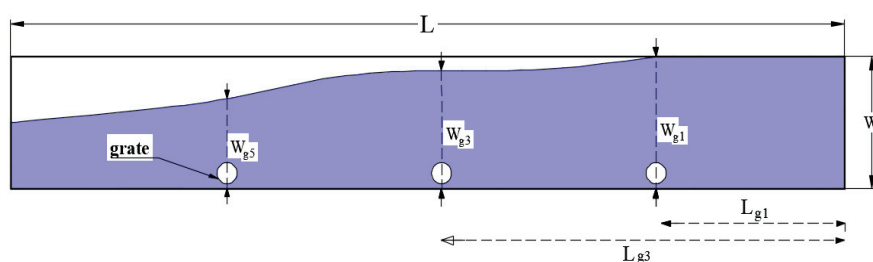


Figure 1. Plan of flume and arrangements of gates.

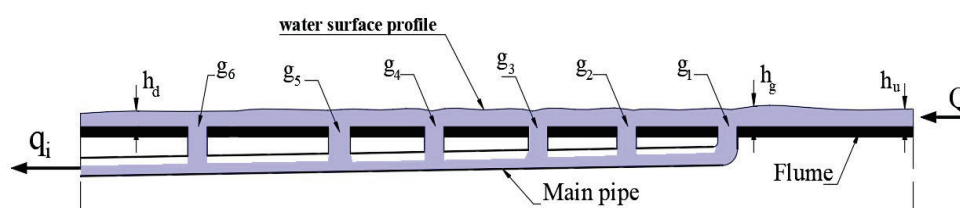


Figure 2. Longitudinal cross-section of flume and main pipe system.

3. Experimental Work

The experimental work was carried out in the hydraulic laboratory at the Faculty of Engineering, Zagazig University. The glass-reinforced plastic moulding flume was used during the experimental tests. The dimensions of the flume are 0.63 m width, 0.10 m depth, and 6.0 m length. The longitudinal slope and cross-section slope are 0.3% and 2%, respectively. A pre-calibrated orifice meter was used to measure the total discharge. A point gauge was used to measure the water depths through the flume length. Three holes were used with radius of 0.05 m at the bottom of the flume over distances 1.08 m and 0.02 m from the edge of the flume. These holes are connected by a pipe with diameter 0.05 m that dispose the drained water to a storage tank with dimension (1.20 m, 0.60 m, 0.60 m) as shown in Figure 3. Five different shapes of grates were used as shown in Figure 4. Moreover, three relative inlet areas of grates (26%, 51%, and 64%) of the best selected grates were used as shown in Figure 5. The time suitable to adjust the total inlet discharge water surface level along the flume in two directions (longitudinal and cross-section) is 30 min.



Figure 3. The shape of flume used in the experimental study.

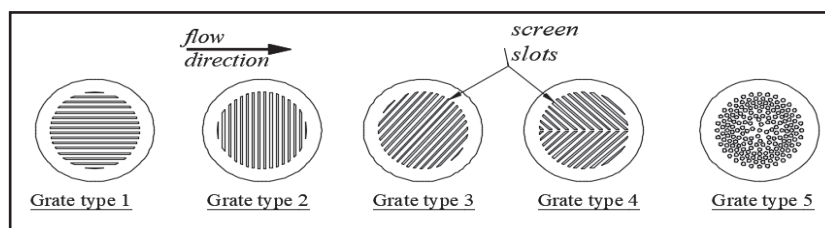


Figure 4. Sketch of different shapes of grates.

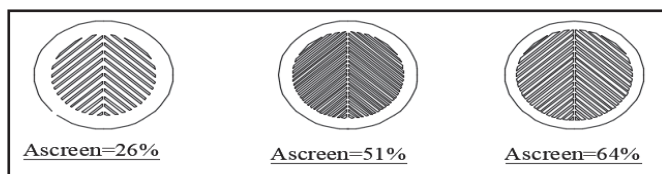


Figure 5. Sketch of different inlet area of grate type 4.

4. Results and Discussion

The experimental work was divided into two stages. The first stage studied the effect of changing the shape of grates on urban rainstorm drainage system efficiency. During this stage, five types of grates were used (Figure 4). The slots of (grate type 1) are parallel to water flow direction, (grate type 2) perpendicular to water flow direction, (grate type 3) make an angle of 45° with the water flow direction, (grate type 4) are diagonal rectangles with a bar in the middle of the grate, and (grate type 5) are circles distributed on the surface of the grate (see Figure 6). The second stage investigated the effect of changing the inlet area of grates on stormwater drainage system efficiency, the relative water depth and the relative water spread width. Through this stage three different relative inlet areas of grates were used (26%, 51%, and 64%) as shown in Figure 5. Two stages were performed with passing discharge from 1.00 to 6.00 L/s.



Figure 6. Grate shapes used in the study.

4.1. The Effect of Changing the Grate Shape on the Efficiency of Urban Rainstorm Drainage Systems

The effect of different grate shapes on the discharge efficiency was studied and the results of the five grate shapes are shown in Figure 7. From the figure it can be seen that the best grate shapes that affected the discharge efficiency are grate type 4 and grate type 1, followed by grate type 2, grate type 3, and grate type 5 was the lowest one. Figure 8 shows the rate of reduction in the discharge efficiency for the five grate types, which also can help in selecting the best grate shape to be used. The results clearly show that the best grate shape is grate type 4 because it provided the lowest reduction in discharge efficiency within 8.70%. This can be explained by the presence of longitudinal and transverse slope in the flume, which leads to a change in the direction of flow for the semi-slant.

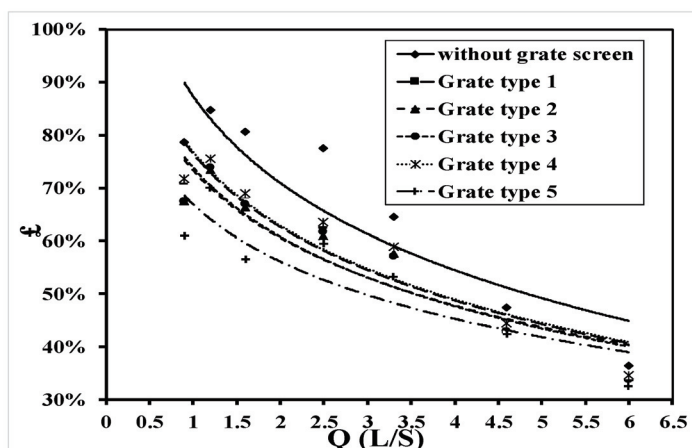


Figure 7. Relationship between discharge efficiency and passing discharge for different types of grate shapes.

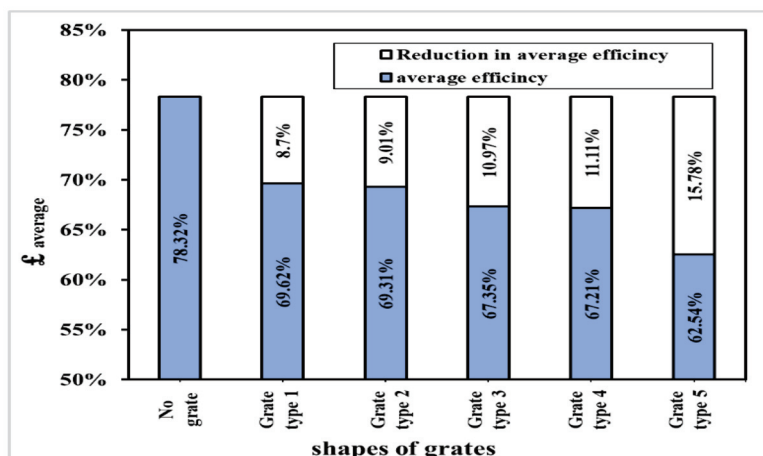


Figure 8. The average discharge efficiency for different types of grate shapes.

Grate shape type 4 mimics the form of water flow at the grate, leading to the opportunity to harvest more water. On the other hand, Manuel [16] investigated that the results of hydraulic design of grate type 1 (with bars parallel to the flow) was better than the hydraulic design of grate type 4. The difference between the two studies is that Manuel used the flume without a transverse slope, and the position of fish bone grate's slots are perpendicular to the flow direction across the width of the flume. This led to produce more splash phenomena than bars parallel that decrease in captured flow as shown in Figure 9. The shape, dimension, and average efficiency of discharge (AEOD) for different types of grates were calculated and are presented in Table 1.

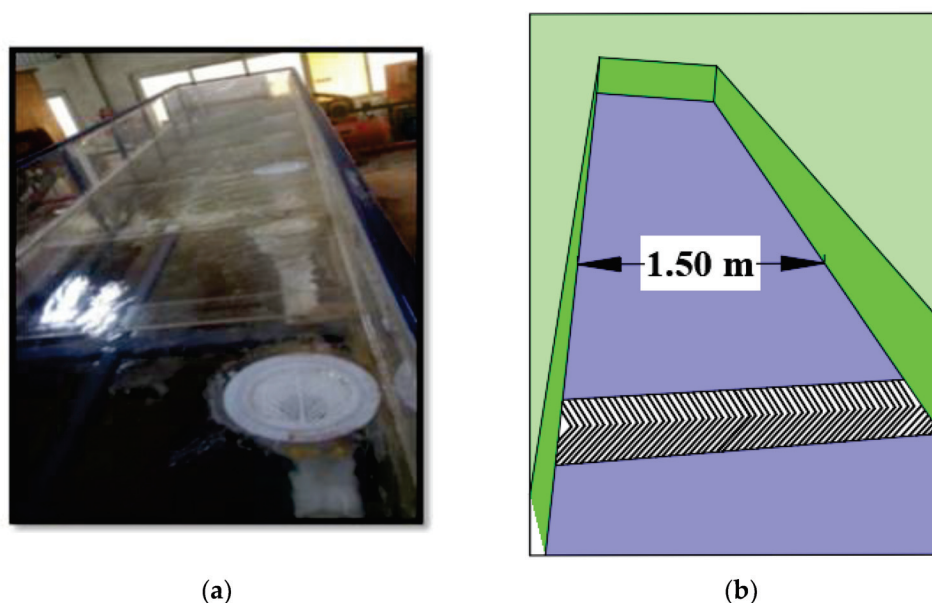


Figure 9. Comparison between grate type 4 in (a) the current study (b) Manuel study [16].

Table 1. The effect of using different grate shapes on the discharge efficiency.

Types of Grate Shape	Shape of Slots	Length of Total Slot (cm)	Width of Slots (cm)	Inlet Area (cm ²)	% Inlet Area	Number of Longitudinal Bars	Number of Transverse Bars	Number of Diagonal Bars	(£) from Q (6.0–1.0) L/s
Grate type (1)	Trapezium	104.8	0.2	21	27%	15	0	0	34.4% to 75.5%
Grate type (2)	Trapezium	104.8	0.2	21	27%	0	15	0	64.2% to 73.3%
Grate type (3)	Trapezium	104.8	0.2	21	27%	0	0	15	33.7% to 73.9%
Grate type (4)	Trapezium	103.8	0.2	20.8	26%	1	0	24	34.6% to 75.6%
Grate type (5)	Circle	—	0.4	21.7	28%	173 circles with diameter 0.4 cm			32.5% to 70%

4.2. The Effect of Changing the Inlet Area of Grates on the Efficiency of Urban Rainstorm Drainage Systems

After choosing the best grate shape (grate type 4) from stage one, different inlet areas of grates were studied with different total discharges. Three different inlet areas of grates (26%, 51%, and 64%) were used to study the effect of changing the inlet area of grates on the efficiency of discharge, relative grate water height, and the relative water width.

4.2.1. The Effect of Changing the Inlet Area of Grates on the Discharge Efficiency

The relationship between efficiency of passing discharge for different inlet area of grate are shown in Figure 10. The results reveal that the grate inlet areas increased from (26% to 64%) and the discharge efficiency increased by 3.48%. Figure 11 shows the results of the average efficiency of discharge and the reductions in efficiency for using different inlet areas. From the results, the average efficiency of discharge for using the grate inlet area (51%, 64%) were very close with a difference of about 1%. The shape, dimension, and average efficiency of discharge for different inlet areas were calculated and are presented in Table 2.

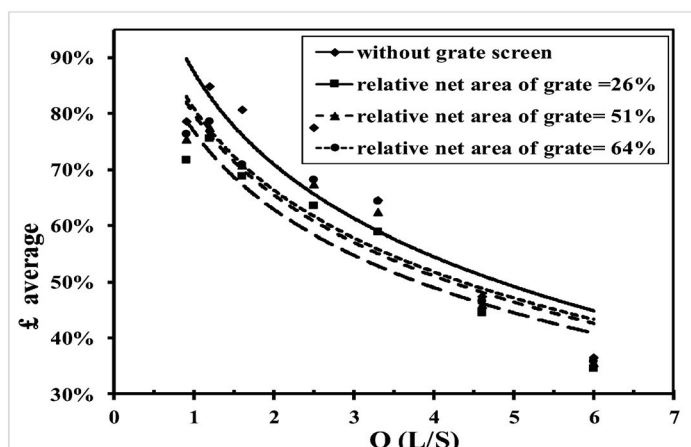


Figure 10. Relationship between discharge efficiency and passing discharge for different inlet areas.

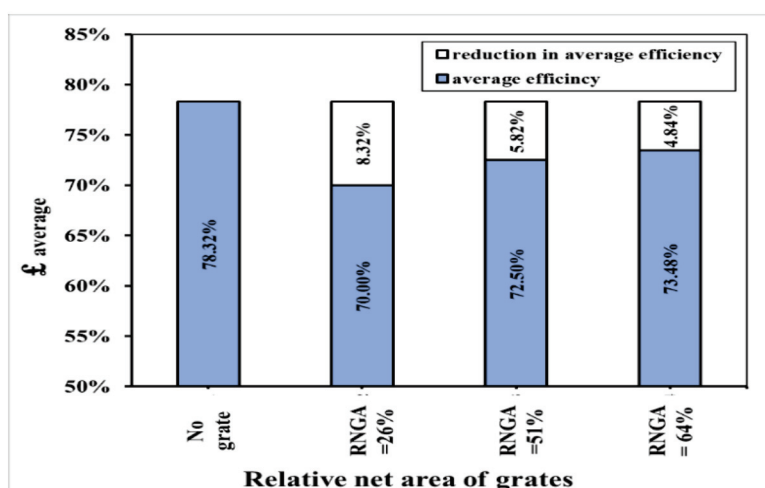


Figure 11. The average efficiency of discharge for different inlet area of grates.

Table 2. The effect of using different inlet area of on the discharge efficiency.

Types of Grates	Length of Total Slots (cm)	Width of Slots (cm)	Inlet Area (cm ²)	% Inlet Area	Number of Longitudinal Bars	Number of Transverse Bars	Number of Diagonal Bars	($\bar{\epsilon}$) From Q (6.0–1.0) L/s
Grate type 4	103.8	0.2	21	26%	1	0	24	34.6% to 75.6%
Grate type 4	168.4	0.2	40.32	51%	1	0	44	35.5% to 77.6%
Grate type 4	201.6	0.3	50.52	64%	1	0	36	26.8% to 78.7%

4.2.2. The Effect of Changing the Inlet Area of Grate on the Relative Grate Water Height

The water depth upstream each grate along the flume was measured to investigate the effect of increasing the inlet area of grate type 4 on water surface profile. Figures 12 and 13 show relationship between relative water height and relative grate distance for using different inlet area of grate (26%, 51%, and 64%) for total discharge (1.20 and 6.00 L/s) respectively. The results indicated that the relative water height of grate increased when grate inlet area 26% was used by (29% and 31%) for inlet discharge (1.20 and 6.00 L/s) respectively. The relative water height of grate decreased by (20% and 7%) at total discharge

(1.20 and 6.00 L/s) for increasing the inlet area of grates from (26%) to (64%) as shown in Figures 12 and 13.

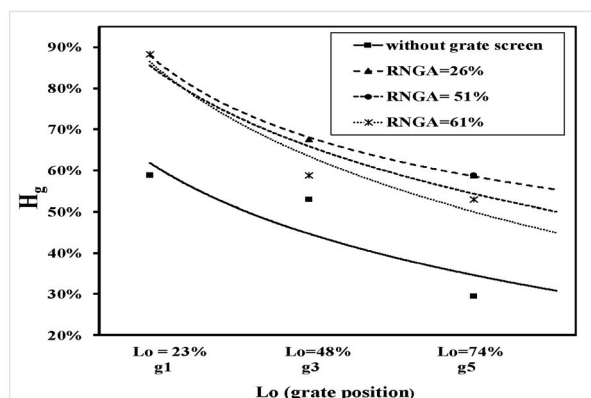


Figure 12. Relationship between relative water height of grate and relative grate distance for different grate inlet areas at ($Q = 1.2$ L/s).

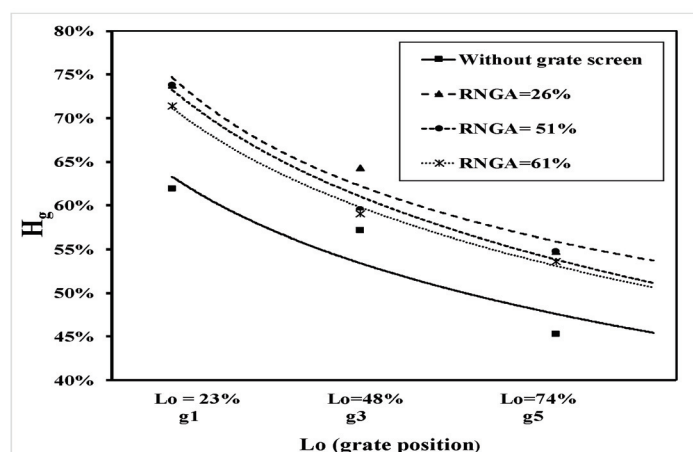


Figure 13. Relationship between relative grate water height and relative grate distance for different grate inlet areas at ($Q = 6.0$ L/s).

4.2.3. Effect of Changing the Inlet Area of Grate on the Relative Water Width

The effect of increasing the inlet area of grates on the relative water spread width was studied by measuring the water spread width along the flume. Figures 14 and 15 show the relationship between relative water spread width and relative grate distance with different grate inlet areas at $Q = (1.20$ and 3.30 L/s). The results indicate that using a grate inlet area with a value of 26% decreased the efficiency by (30% and 14%) using $Q = (1.20$ and 3.30 L/s), respectively. This decreases due to preventing excess water from passing through grate slots. On the other hand, this negative effect decreased by increasing the inlet area of the grate from 26% to 64% by (4% and 9%) for using $Q = (1.20$ and 3.30 L/s), respectively, as shown in Figures 13 and 14.

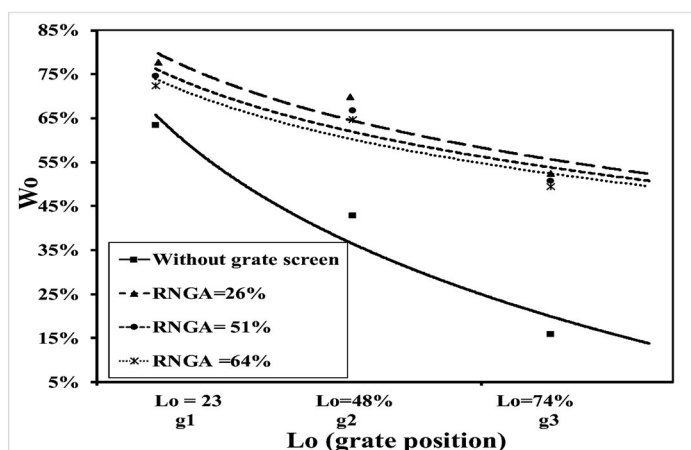


Figure 14. Relationship between relative width and relative grate distance for different grate inlet areas ($Q = 1.2 \text{ L/s}$).

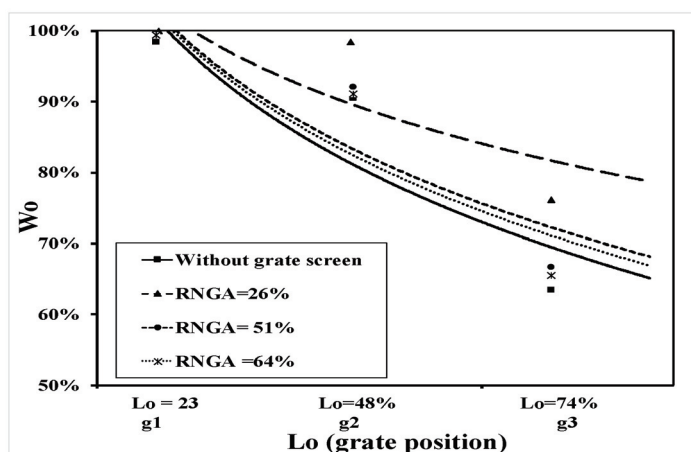


Figure 15. Relationship between relative width and relative grate distance for different grate inlet areas ($Q = 3.3 \text{ L/s}$).

5. Prediction of the Discharge Efficiency

An empirical equation was developed to correlate the discharge efficiency ($\mathcal{E}$) of urban rainstorm drainage systems to a number of parameters such as total discharge, the relative grate length, the relative grate width, the relative grate height, and the relative grate inlet area. The measured data in the laboratory with dimensional analysis and multi regression analysis were used to develop the empirical equation to correlate the water discharge efficiency ($\mathcal{E}$) to other parameters based on Equation (1). The discharge efficiency ($\mathcal{E}$) is expressed as the following:

$$\mathcal{E} = 0.77289Q - 0.08A_g + 0.134 \quad (2)$$

where A_g is the relative grate area, Q is the flume discharge (L/s), and $\mathcal{E}$ is the system discharge efficiency.

The correlation coefficient and the standard error of for Equation (2) are 94% and 0.04, respectively. Figure 16 shows the relationship between the predicted values of $\mathcal{E}$ using Equation (2) versus the measured value while Figure 17 shows the distribution of the residuals around the line of zero error. Both figures indicate that Equation (2) represented the measured data very well and hence can be used to predict the efficiency of a different number of grates for passing discharge ranging from 1.00 to 6.00 L/s.

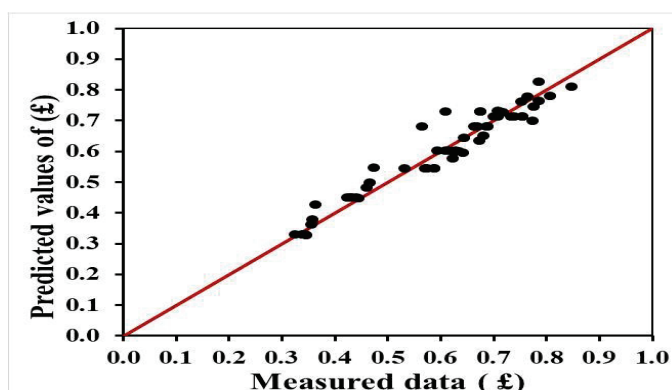


Figure 16. Measured £ versus predicted values from Equation (2).

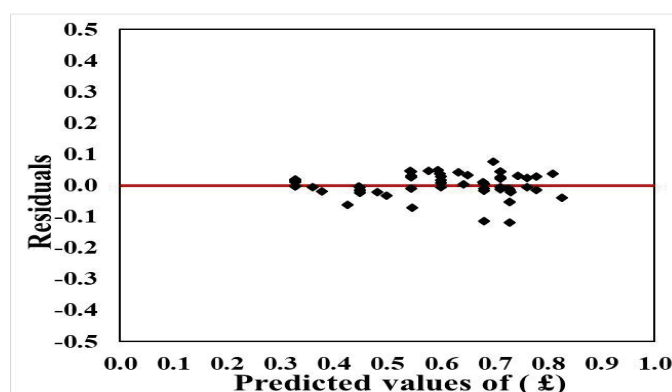


Figure 17. The distribution of residuals around the line of zero error for predicted values of £.

6. Conclusions

Improving the efficiency of road drainage systems depends on studying the hydraulic behavior of different parts of the drainage system. This study presents an experimental work to investigate the effect of changing the grates' shape and size of inlet area on the hydraulic efficiency of urban rainstorm drainage systems. The study examined five different grate shapes and three different inlet areas of grates. The efficiency of rainstorm discharge system for using five types of grate shapes (type1, type2, type3, type4, and type5) was (69.31%, 67.35%, 67.21%, 69.62%, and 62.54%), respectively. The best grate shape is (grate type 4) for the smallest reduction in efficiency of discharge within 8.7%, due to the presence of longitudinal slope of 0.3% and transverse slope of 2% in the flume, which changed the direction of flow for the semi-slant, especially in the area of grates. Therefore, grate shape type 4 mimics the form of water flow at the grate, leading to the opportunity to harvest more water. The efficiency of the water discharge system using three grate inlet areas (26%, 51%, and 64%) was (70%, 72.5%, and 73.48%), respectively. The relative grate height decreased as the area of grate increased by (20% and 7%) at total discharge (1.20, 6.00 L/s), increasing the relative inlet area of the grate's screen from (26%) to (64%), which provided minimum grate slots a negative effect of flow. This negative effect decreased by increasing the inlet area of grates from 26% to 64% by (4% and 9%) for using discharge of (1.20 and 3.30 L/s), respectively. Multi regression analysis and dimensional analysis principle were used to develop an empirical equation to estimate the efficiency of urban rainstorm drainage systems in correlation to grate shapes and the relative inlet area of the grates. This empirical equation can be used by the decisionmakers to monitor the situation of grate blockage and system efficiency. However, a three-dimensional simulation of the drainage system including other variables such as changing pipe diameters, slopes, and surface roughness are recommended for future studies. The results of this study can be

used to improve the urban rainstorm drainage systems' efficiency and can reduce flood risks in urban areas, especially on roads.

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MDPI AG
Grosspeteranlage 5
4052 Basel
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