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Planning Models in Designing Wastewater Management Systems: A Systematic Review

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Several issues related to designing and operating wastewater and sanitation systems have become more complex in emerging economies like the Philippines. The challenge of such sustainable wastewater management or a lack thereof is characterized by interrelated political, economic, social, technological, environmental, and legal factors where rapidly growing population and urbanization are exacerbating the challenges. The selection of the most appropriate technique to assess the system's current state and design a resilient and sustainable wastewater system is deemed necessary. This paper aims to provide a PRISMA-guided systematic review to synthesize and analyse the existing literature on the application of planning models to wastewater management systems. A comprehensive search of relevant databases, such as Scopus and Google Scholar, is applied to identify initially relevant studies. A total of 3178 studies were identified from the search for the last 15 years (2007-2022) using the keywords "planning model" AND "wastewater management systems" OR "planning models" AND "wastewater management" OR "waste_water management." The result of the systematic review shows limited planning methodologies that could address uncertainty in the design of wastewater management systems.

1. Introduction

Planning is a critical step to achieving management system objectives. Planning models help stakeholders provide the best strategies that will optimize limited resources. Over the years, developing the most appropriate model for wastewater management systems gained significant interest from various researchers. Wastewater management systems involve collecting, treating, and reusing wastewater (Roozbahani, 2021). Managing wastewater collection networks requires careful planning strategies to avoid undesirable economic, environmental, and social effects. The selection of the most suitable wastewater treatment process for municipal and industrial wastewater is constrained by available technology and the high costs of facilities and equipment. Activated sludge is one of the most common types of wastewater treatment applied to municipal wastewater (Englande et al., 2015). The study by Singh et al. (2021) stated that activated sludge is also a conventional process used in sewage water treatment for removing some pharmaceutical compounds. Deciding whether to decentralize or centralize the wastewater treatment plant is also one of the significant challenges for decision-makers (Zheng, 2016). The implementation of decentralized wastewater systems in municipalities may create health and environmental risks because of poorly maintained onsite wastewater system facilities (Connelly et. al., 2023). The cost comparison of both wastewater management systems may depend on land requirements and population density. Another issue that needs to be addressed is implementing wastewater reuse in a particular community. Selecting the factors to be considered when assessing the suitability of wastewater management systems needs careful study.

The factors to consider in the choice are divided into two general criteria. First, the physical factors include land availability and use, topography, soil, climate, and energy resources. The availability of space to build the infrastructure is crucial in planning. It has an enormous impact in terms of construction costs. Anagnostopoulos and Vavatsikos et al. (2012) mentioned that the high costs of land use are attributed to the lithology, soils, and rock classifications. The lithology criteria are classified based on geological formations. Second, the social factors consider the density of the population, funds, and skills available within the community, affordability, and

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willingness to pay for the selected technology (Tokich, 2006). These factors are relevant in establishing planning models for wastewater management systems. Uncertainty about these factors plays a more significant role in designing planning models for wastewater management. The effects of population growth, climate change, and the demand for water use must be considered in the model. As mentioned in the study by Amadi (2012), population and urban growth drive the increasing demand for the reuse of treated wastewater.

Climate change remains one of the challenges in wastewater management systems in the twenty-first century (Singh and Tiwari, 2019). Tolkou and Zouboulis (2015) categorizes the impact of climate change into two, indirect which may be associated with water conservation, and direct which affects the wastewater infrastructures. Although most wastewater managers show concern about the impact of climate change, only a few of them are keen on adapting it in future wastewater policy (Kirckchoff and Watson, 2019). There is still a gap in understanding the impact of climate change on urban sanitation infrastructure and service systems (Hyde-Smith et al., 2022). Porse et al. (2023) mentioned that there is limited research on adaptive planning on wastewater systems that considers future challenges such as climate change, growing population, and water consumption rates. Hughes et al. (2021) highlighted the impact of climate change, such as the implication from nuisance flooding, spills, and odour, deterioration of water quality because of uncontrolled wastewater discharges, increasing damage to wastewater infrastructure that can result in loss of income, and increased costs to stakeholders. Uncertainty about climate change has a significant effect on the social costs of wastewater treatment, in such a case, people residing in the highly urbanized area may have a higher demand for clean water which requires a more sophisticated wastewater treatment system (Reznik et al., 2020).

The literature review explores the current trends and emerging issues in the application of planning models in wastewater management systems. The review is guided by research questions shown in Table 1.

Table 1: Research questions on the planning models in designing WW management systems

Research Questions (RQ)
1 What is the research trend in developing planning models applied to wastewater management systems?
2 What are the most common model approaches used for planning wastewater management systems?
3 What is the main purpose of developing planning models for wastewater management systems?

The remainder of the paper is organized as follows. Section 2 provides the methodology used for the systematic review, including the criteria for article eligibility. Section 3 describes critical review results on the research trends and the planning model approaches applied to wastewater management systems. The last section provides the conclusions and future research potentials in wastewater management systems.

2. Methodology

A systematic review was conducted using the guidelines provided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology (Moher et al., 2009). The review process was documented using the PRISMA flow diagram shown in Figure 1. Scholarly electronic databases such as Google Scholar and Scopus were used to identify original research published in reputable journals from years 2007 to 2022. The PRISMA flow diagram has four stages. The first stage is called the Identification of articles for review. In this study, relevant articles from the databases were searched using a combination of the following keywords:

“Planning model” AND “wastewater management systems”
OR “planning models” AND “wastewater management”
OR “waste_water management”

A total of 2356 articles were returned from the Google Scholar database search and 822 records from the Scopus database. Duplicates, articles using a language other than English, and those with no specific publication declared and no specific authors mentioned were removed for initial screening. In the second stage, screening, a total of 2430 articles were screened based on their relevance to the systematic review. The review did not consider the articles published from book or book chapters, literature reviews, conferences, theses, and case studies. Articles were also screened based on the title. A total of 1358 articles were removed based on the title review. The articles that do not contain specific planning models applied to wastewater management systems were removed. In the third stage, eligibility, about 489 irrelevant articles were excluded from the abstract and full-text review. These articles were found to be beyond the scope and do not show any relevance to the review objectives. After excluding all irrelevant studies from full-text screening, the fourth and last stage of screening identified only 32 articles eligible for the systematic review.

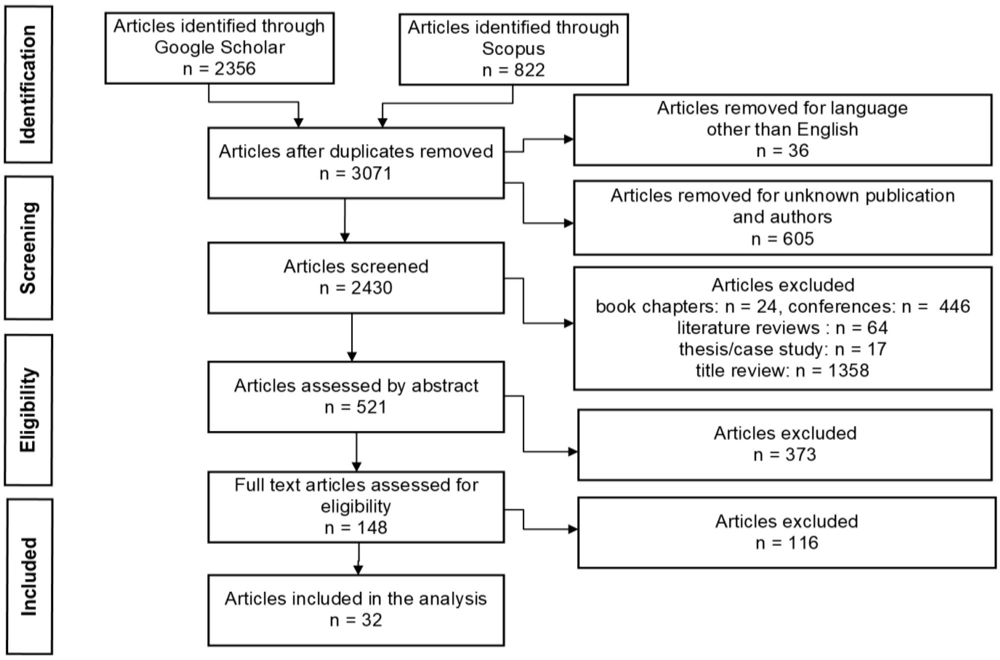

Figure 1: PRISMA flow diagram for a systematic review of planning models in designing the WW system

3. Results and discussion

3.1 RQ1: What is the research trend in developing planning models applied to wastewater management systems?

The trend in Figure 2 shows a continuing interest in developing planning models applied to wastewater management systems. After the full-text review of 148 papers, only 32 articles are found to be relevant based on the research scope. The articles were assessed based on the approaches of planning models and the application of these approaches to solve problems in wastewater management systems.

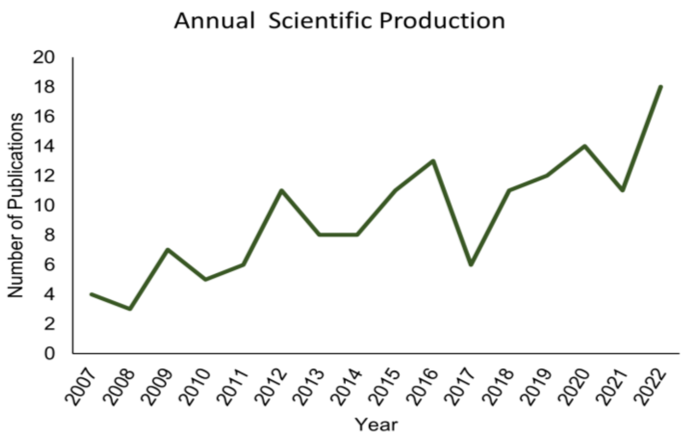

Figure 2: Yearly publications on WW management systems based on full-text eligibility screening

3.2 RQ2: What are the most common model approaches used for planning wastewater management systems?

The results in Figure 3 shows that the most popular approach for planning wastewater management systems is using Multiple-Criteria Decision Making (MCDM), particularly the Analytic Hierarchy Process (AHP), followed by Fuzzy-based MCDM and Systems Dynamics (SD). In the study of Kalbar et al. (2013) , AHP is applied to reconcile multiple quantifiable and qualitative sustainability indicators. Hadipour et al. (2016) implemented AHP in selecting wastewater reuse applications. This study's criteria are technical, economic, social, and environmental. Quality of effluent is considered in the technical aspect, while economic criteria include income generation, financial opportunities, capital, and operational costs. Public acceptance, health risks, social benefits, and government support belong to the social criteria. The environmental criteria considered environmental benefits, ecological risks, and water reservation. Mirabi et al. applied four multi-attribute decision analysis tools - TOPSIS, ELECTRE, HWA, and ANP, to select the wastewater treatment process. Anagnostopoulos et al. (2007) introduced the four-level evaluation hierarchy to select the optimal wastewater treatment plant. The second level of criteria involves the economic, environmental, and social aspects. Under the environmental criteria are performance, sludge production, and flow fluctuations. The social criteria considered odor problems and aesthetics. The different cultural backgrounds of respondents, which provide a level of uncertainty in the response, led Dursun (2018) to propose a fuzzy MCDM approach combining TOPSIS and DEMATEL to determine the most suitable wastewater treatment alternative. Systems Dynamics (SD) was first applied to model the water and wastewater network management in Canadian water utilities (Rehan et al., 2011). The study helps to create new regulations in the long term. Mohammadifardi et al. (2019) developed an SD model to understand the relationships between wastewater collection and wastewater treatment plants. The model has extended the scope to consider the environmental consequences of decisions related to asset management planning of wastewater infrastructure systems. Prouty et al. (2020) considered the impacts of climate change in developing the SD model for wastewater infrastructure transitions. Cunha et al. (2009) developed a robust optimization model, considering the nonlinear cost functions of installing sewer networks. A large population density within the region characterizes the model. A simulated annealing algorithm was used to run the model. Another robust optimization approach was used by Kang et al. (2013) to address uncertainties in input parameters. Different scenarios were presented considering the variations in the water demand. Gikas et al. (2015) enhanced the MILP model approach to calculate the optimum water and wastewater infrastructure design. The model introduced a new binary variable representing wastewater flowing from different locations. Few researchers considered non-linear optimization models, stochastic modeling, knowledge-based approach, and mathematical programming in planning wastewater management systems. Cunha et al. (2009) applied a mixed-integer non-linear optimization model to determine the optimal configuration considering the layout of sewer networks and the location of treatment plants. Huang et al. (2015) developed a multi-objective optimization model for designing an integrated urban wastewater system. A multi-scale two-stage mixed integer stochastic model developed by Jing et al (2017) indicated optimal results considering the multiscale nature of wastewater treatment plant networks.

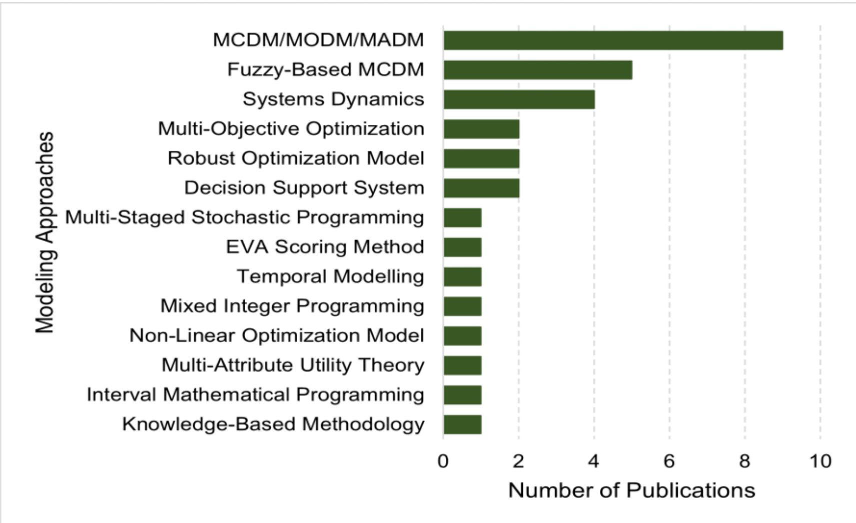

Figure 3: Modelling approaches used in planning WW management system

3.3 RQ3: What is the main purpose of developing planning models for wastewater management systems?

Figure 4 highlights the purpose of developing different planning models for wastewater management systems. Most research on planning models proposed methodologies to guide the stakeholders in selecting appropriate wastewater treatment plants. Karimi et al. (2011) mentioned that the application of MCDM is essential in selecting an appropriate wastewater treatment plant. The diversity of industrial wastewater and the local condition of effluent sources necessitates considering multiple criteria in decision-making. The rapid increase in the demand for wastewater treatment has led Baserba et al. (2012) to implement a knowledge-based methodology for designing a suitable wastewater treatment process. Inadequate decision support tools have led Avramenko et al. (2010) to develop a fuzzy-based decision support method to select sustainable wastewater treatment technologies. The rapid increase in environmental, economic, and social challenges has led Buyukozkan and Tufekci (2021) to develop a multi-stage fuzzy decision model to assess the appropriate wastewater treatment system.

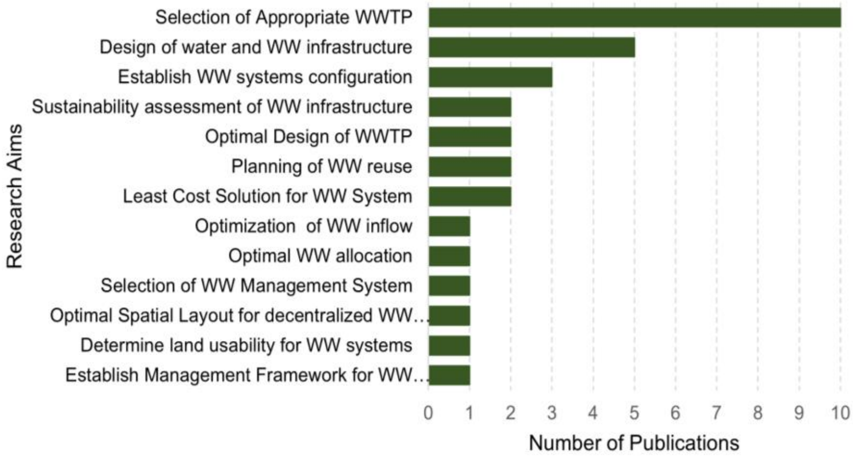

Figure 4: Research aims of the reviewed applications

4. Conclusions

Wastewater management is vital to protect the environment, reduce human health risks, and provide better alternatives for agricultural and industrial use. Planning models are essential to guide stakeholders in selecting appropriate collection, treatment, and reuse processes. This paper utilizes the PRISMA framework to show the development of planning models applied to wastewater management systems. Multicriteria decision analysis is commonly used in designing wastewater infrastructure or in the selection of wastewater treatment systems. It helps decision makers establish strategies by evaluating various alternatives derived from the model. However, the integration and interaction among the dynamic constraints involving climate change, population, and urban growth were not captured in the previous models. The result of the review unveils future research potentials in establishing optimal decision rules and policy leverages for more efficient wastewater systems. Future researchers may consider developing a hybrid simulation model to establish a more sound policy related to wastewater management systems.

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