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Vol. 32 (3) **2023** **Issue 101**

Contents

Wydawnictwo SGGW, Warsaw 2023

Wydawnictwo SGGW   wydawnictwosggw

Editorial work – Anna Dołomisiewicz, Violetta Kaska

ISSN 1732-9353 (suspended)   eISSN 2543-7496

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Developing an empirical model for assessment of total nitrogen inflow to rivers and lakes in the Biebrza river watershed, Poland

Keywords: nitrates, hydrology, agriculture, eutrophication, catchment

Introduction

In recent years, the discharge of nutrients has been identified as a significant cause of pollution in European water resources, affecting both drinking water and aquatic ecosystems (Grizzetti et al., 2017). While agriculture is a primary contributor to this issue, other sources, including human and industrial wastewater effluent, also contribute to the problem (Wuijts, Fraters, Boekhold & van Duijnen, 2022). However, crop production has been the largest contributor to the increase of the amount of nitrogen entering in the biospheric cycle (Sutton et al., 2011). Moreover, European vegetable production systems overused it, based on the experience of growers and technical advisors. It leads to nitrate leaching and eutrophication of surface water bodies (Thompson, Incrocci, van Ruijven & Massa, 2020), and the leaching of nitrogen from the surface into surface water bodies is a common form of diffuse nitrogen pollution that contaminates water resources (Almasri, 2007). Where the

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main source of nitrogen is based on the use of fertilizers, with Europe and Asia being the main producers of nitrogen fertilizers (Llive et al., 2015). It is important to note that plants cannot take advantage of all the nitrogen present in the soil, which has significant implications. The amount of nitrogen that is used can vary from 25% to 85%, depending on the type of crop and the agricultural techniques used (Ávila & Sansores, 2003). Be that as it may, the deterioration of water quality is a global issue, and everyone contributing to pollution, including agriculture, industry, transport, and amenity managers, must be made aware of this fact (Knapp, 2005).

In addition, to maximize crop production, an excessive amount of nitrogenous fertilizer is often applied to the soil, significantly increasing nitrogen loss through stormwater, according to report by the Pan American Health Organization and the World Health Organization in 1980 (Ávila & Sansores, 2003). Due to all mentioned factors, the European Union (EU) has implemented ambitious water policies aimed at safeguarding and revitalizing aquatic ecosystems through the Water Framework Directive and the Marine Strategy Framework Directive (Grizzetti et al., 2021). Currently, over 50% of water bodies in the EU do not meet the ecological standards mandated by the Directive 2000/60/EC (so-called Water Framework Directive), with nutrient enrichment being a primary contributor to the degradation (Poikane et al., 2019). Likewise, chemical pollution (49%) is the main impact on surface water bodies, followed by altered habitats due to morphological changes (40%) and nutrient pollution (28%). This nutrient enrichment causes eutrophication, which in turn leads to the loss of aquatic biodiversity (Bednarek, Szklarek & Zalewski, 2014). What is more, excessive nutrient enrichment can be dangerous for human health, e.g. owing to toxic algal blooms, and can impair the use of water for drinking and bathing (*EEA Report*, 7/2018).

The case of Biebrza river is identical, where historically people used to cultivate this area for agricultural purposes. However, since 1960, these activities have increased significantly due to the discontinuation of traditional farming practices like hand mowing and livestock grazing. In fact, some parts of the wetlands were even drained to make way for farming (Sucholas, Molnár, Łuczaj & Poschlod, 2022). Also, it is important to mention that the Ramsar Convention has designated the Biebrza river as a wetland site of global significance (Dembicz, Kozub, Bobrowska & Dengler, 2020), it is the largest peatland complex in western and central Europe, and its peat soils have undergone degradation due to human activities (Razowska-Jaworek & Sadurski, 2014). The valuable ecosystems in this place are not just limited to natural peatlands, but also include large open semi-meadows resulting from extensive agriculture. When there are changes in water conditions or extensive agriculture is discontinued, the meadows and pastures undergo a transformation into tall herb vegetation and eventually, reed. In some parts of the Biebrza river valley, this process leads to the succession of shrubs and forest over the non-forest ecosystems of peatlands (Świątek, Szporak, Chormański & Okruszko, 2008). Some of its tributaries have been modified to be drainage channels or to regulate their flow (Okruszko, 2005). When these soils are drained, they can release significant amounts of nitrogen and other nutrients into water bodies. Peat soils can store significant amounts of nutrients such as nitrogen. The cessation of agriculture has also allowed the growth of bushes and trees, further accelerating the degradation of peat soils and the release of mineral nitrogen into groundwater (Razowska-Jaworek & Sadurski, 2014).

Therefore, as nitrogen fertilizers are not fully absorbed by crops, it is important to describe an approach to control such loss before it enters the river basin, and thus substantially reduce the nitrogen load (Cai et al., 2014). Although several empirical models for modeling nutrients discharge to surface water exist (Naturstyrelsen, 2014), it has been observed that its application may not be universal, as the field observations may deviate significantly from the model predictions in certain cases. Mathematical methods are commonly used in connection with measured data for the evaluation of water quality (Pei-Yue, Hui & Jian-Hua, 2010). Even models based on the geographic information systems (GIS) have been developed to simulate nitrogen inputs in lakes such as the InVEST model (Yang et al., 2019). Although physical models have made significant progress in evaluating nitrogen load (Tan et al., 2023), their application is limited due to the need for extensive data and their accuracy (Duan et al., 2013). Hence, developing a scientifically based assessment model for the prediction of nitrogen is crucial for identifying sources of nitrogen and for preventing and controlling pollution in the watershed (Tan et al., 2023).

It is the same condition as for the rivers in the Biebrza watershed, lakes also have a pivotal role in contributing to the reduction of nutrients. The characteristics of lakes allow for an expansion of physical, chemical, and biological processes to predict the responses of large lakes based on the results from smaller ones (Schindler, 2012). Lakes are depositional environments, and the material that accumulates in the sediments of these water bodies can be deposits from outside the watershed (Downing et al., 2008). It can act as sinks for nutrients, absorbing and storing large amounts of nitrogen in their sediments and water. Additionally, they can provide a habitat for organisms that feed on nutrients, such as phytoplankton and zooplankton, thereby reducing the amount of nitrogen available in the water (Rekha, Raj, Aparna, Bindu & Anjaneyulu, 2005). Consequently, it is important to analyze the behavior of rivers and lakes in Biebrza. Therefore, there is a need to develop a location-specific empirical model that can effectively capture the site-specific factors that influence the nitrogen loss. In this study, we propose a modified empirical model using field observations to estimate the total nitrogen load in the Biebrza catchment in the rivers and lakes. The modified model is expected to provide more accurate predictions by incorporating the site-specific factors that influence the nitrogen load and it will provide valuable information for better managing and protecting the water resources in the region.

Material and methods

Site description

The Biebrza river is reputable as the most significant and invaluable riverside ecosystem in Europe. Its catchment area spans a vast expanse of approx. 7,250 km^2 with a length of 164 km in northeast Poland (Fig. 1), making it one of the region's most extensive catchments. Comprising a mix of agricultural land, forests, wetlands, and mires, agriculture dominates the land use of the catchment. Furthermore,

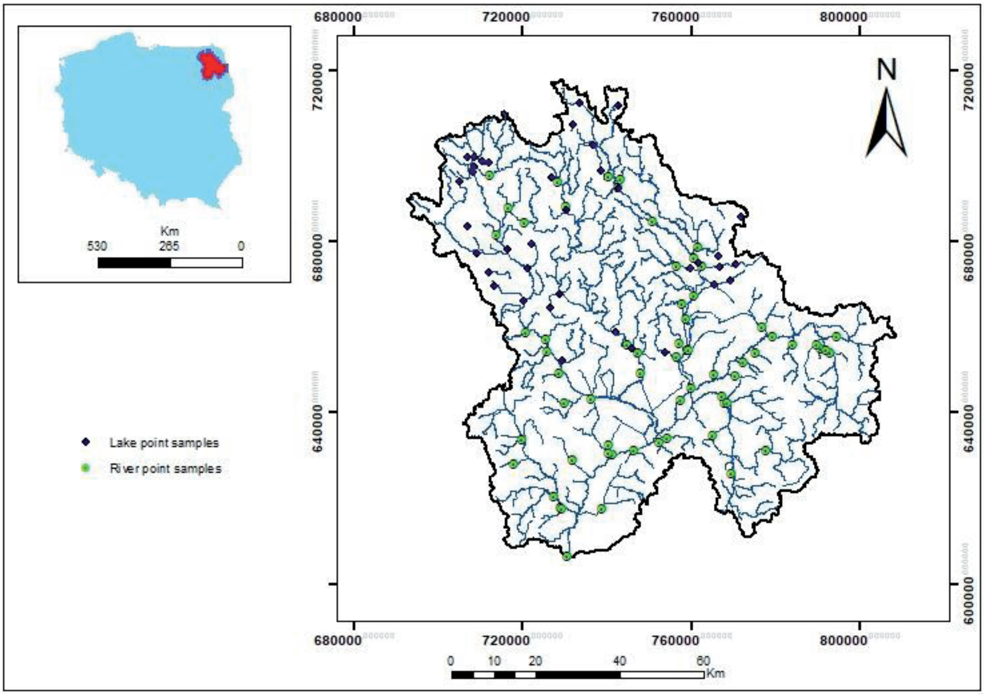

FIGURE 1. Location of study area in Biebrza catchment and the monitoring points in the rivers and lakes from 2005–2021

Source: own elaboration.

the catchment area houses several protected areas, such as the Biebrza National Park and the Narew National Park, that are integral to maintaining the ecological balance of the river and its surrounding environment (Wassen, Barendregt, Palczynski, de Smidt & de Mars, 1992). Nonetheless, environmental pressures, including land use changes, pollution, and climate change, can impact the water quality and ecological health in this area, warranting comprehensive monitoring and management of the catchment. The Biebrza river catchment is a major source of nutrients to the Baltic Sea, with significant inputs of nitrogen and phosphorus from agricultural and urban sources, resulting in eutrophication and reduced water quality (Xu et al., 2021).

According to Figure 2, both in the rivers and lakes, the highest load of nitrogen accumulates in the central part of the Biebrza river basin, represented by the red color. Given that the empirical model is mainly based on agricultural pollution, there are other parameters that were not considered and could have influenced these high concentrations, such as emissions from factories, vehicles, and burning of fuels, leaching from livestock manure, leachate percolation

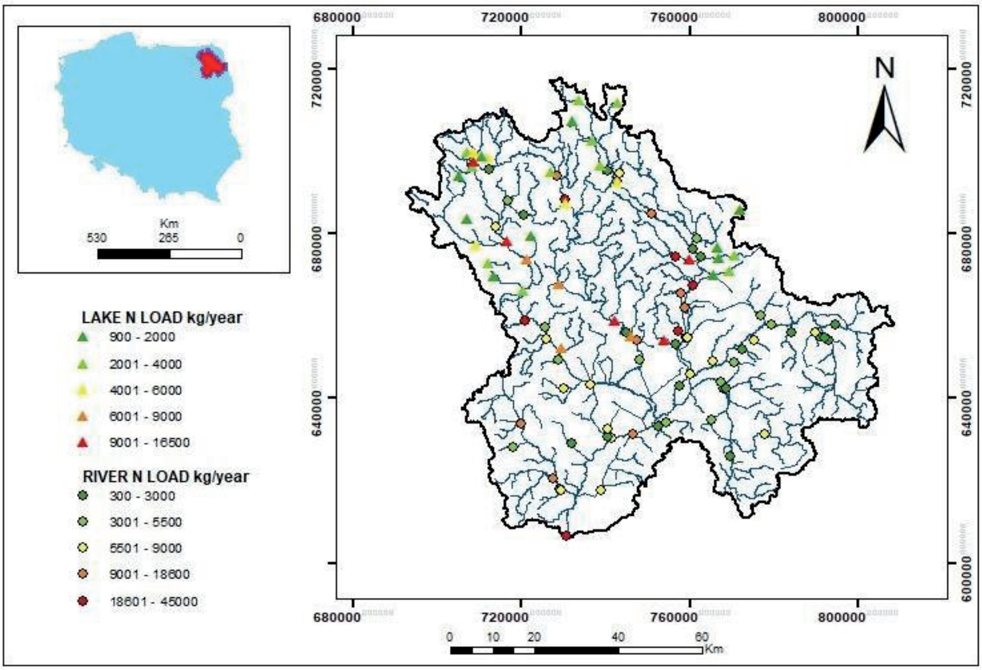

FIGURE 2. Location of study area in Biebrza catchment and the nitrogen load in the rivers and lakes from 2005–2021

Source: own elaboration.

from landfills, or discharge of wastewater (Silva, Cobelas & Gonzáles, 2017). Meanwhile, in the northern part of the basin, the nitrogen load varies between intermediate values. It is in these areas that agriculture covers most of the sub-catchment. However, in the southern part, most of the samples taken show low nitrogen values, where the agricultural area covers a smaller surface area of the sub-catchments in these areas.

Nitrogen load modeling

An empirical model is a mathematical representation of a real-world system, developed through observation or experimentation. Empirical models are used in scientific research and engineering to describe complex systems and make predictions about their behavior. The accuracy and the utility of an empirical model are dependent on the quality and quantity of data utilized in its development, as well as the assumption and simplifications made during the modeling process. Empirical models are iteratively refined and enhanced over time as new data becomes available and the underlying understanding of the modeled system evolves.

The total nitrogen loss was estimated using the empirical model provided by Naturstyrelsen (2014; Eq. 1):

$$N_{loss} = 1.124 \cdot \exp[-3.080 + 0.758 \cdot \ln(H) - 0.0030S + 0.0249D], \tag{1}$$

where N_{loss} is the nitrogen loss, measured in kg·ha^{-1}·year^{-1}, H is the annual runoff, measured in mm, S is the percentage of sandy soil, where the shapefile of global hydrologic soil groups (HYSOGs250m) for the curve number-based runoff modeling was used and processed in ArcTools, D is the percentage of agriculture, obtained from the TIFF Corine Land Cover – 100 m in 2018, the same that was converted into shapefile to be processed in ArcGIS.

Once the equation was applied, it was obtained an average nitrogen loss of 5.85 kg·ha^{-1}·year^{-1} and 6.2 kg·ha^{-1}·year^{-1} for rivers and lakes respectively, nitrogen total load is the total nitrogen loads in kg·year^{-1}, nitrogen total load can be calculated by nitrogen loss multiplied by the area of the sub-catchment of each motoring point, measured in ha.

Due to the lack of data on the discharge of the river, the formula of the rational method was applied for the calculation of the discharge average.

$$Q = C \cdot P \cdot A, \tag{2}$$

where Q is the average annual discharge, measured in $m^3 \cdot year^{-1}$, C is the runoff dimensionless coefficient obtained in 17 area Biebrza sub-basins, which data from the research by Venegas, Marcinkowski, Piniewski and Grygoruk (2022), P is the annual precipitation, measured in m, which was observed from 1951–2021 that were sourced by the input data set of meteorological data on rainfall totals were daily data from hydrological and meteorological monitoring (IMGW-PIB), which were summed up to individual calendar years.

These data were determined using the data of the characteristics of water balance components, raw water balance in water gauge catchments and within the boundaries of the Biebrza National Park and its buffer zone (Venegas et al., 2022), for each monitoring point. Variable A is the area of the sub-catchment determined for each sample point c. For this, the DEM image was downloaded in the STRM (Shuttle radar topographic mission). The outcomes derived from the application of the empirical model will be compared against the observational data obtained from the Regional Inspectorate of Environmental Conservation (*Wojewódzki Inspektorat Ochrony Środowiska*). The comparison will be predicted in the respective nitrogen load trends, the percentage deviation in nitrogen load between the nitrogen loads predicted by the empirical model and those obtained from the observational data, the mean nitrogen load values, and an array of statistical techniques such as the correlation coefficient, determination coefficient, and root mean square error. The original empirical model was calibrated by means of a trial-and-error process utilizing the square root method, based on data spanning the timeframe of 2005–2015 for rivers and 2008–2019 for lakes. The validation of the empirical model is carried out utilizing the data from 2016–2021 for rivers and 2020–2021 for lakes.

Results

Calculated total nitrogen loads

The calculations were derived from data obtained from 234 samples for rivers and 41 samples for lakes situated in the Biebrza river region. Total nitrogen load is expressed in $kg \cdot year^{-1}$, and it was calculated by Eq. (2) and multiplied by the data obtained from monitoring the water quality from the Regional Inspectorate of

Environmental Conservation. Nitrogen load observed is compared with the existing equation results. The values obtained from these calculations can be used to establish new equations that close the observed nitrogen loads results.

The results obtained from the use of the empirical model, its calibration and validation are shown in Figure 3. Nitrogen data taken in 2005 and 2015 were used to calibrate the model using linear regression. Figure 3a shows the observed nitrogen load and the calculated one using the empirical method Eq. (1), while Figure 3b shows the calculated nitrogen load and the calibrated model (Eq. 3). In Table 1, the coefficient of determination (R^2) has the same value, the calibrated model presents a steeper slope, and the data are also distributed better. Figures 3c and 3d show the data from 2016 to 2021, which were used to validate and determine the operation of the new empirical model, where the R^2 has a higher value, which implies a significant improvement. For the validated data (0.82), R^2 is higher than that calculated one for the calibrated data (0.81). Furthermore, the accuracy of the model improved

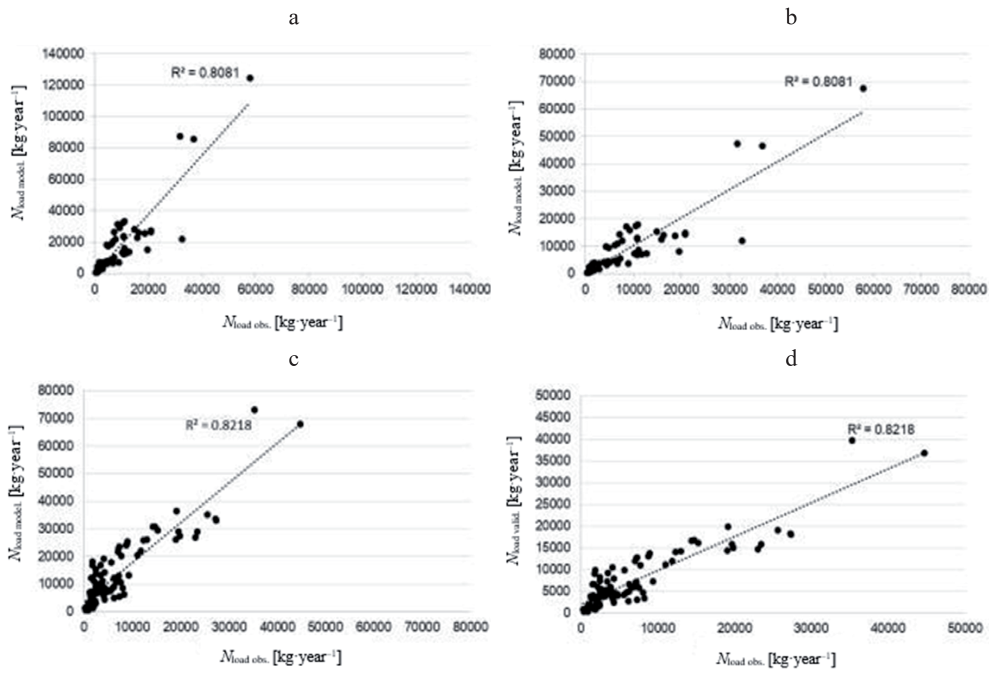

FIGURE 3. Linear regression of rivers monitoring points: a – nitrogen load observed ($N_{\text{load obs.}}$) and nitrogen load modeling ($N_{\text{load model.}}$) in 2005–2015; b – nitrogen load observed ($N_{\text{load obs.}}$) and nitrogen load calibrated ($N_{\text{load calib.}}$) in 2005–2015; c – nitrogen load observed ($N_{\text{load obs.}}$) and nitrogen load modeling ($N_{\text{load model.}}$) in 2016–2021; d – nitrogen load observed ($N_{\text{load obs.}}$) and nitrogen load validated ($N_{\text{load valid.}}$) in 2016–2021

Source: own elaboration.

significantly as the root mean square error (*RMSE*) value decreased for both calibration and validation (Table 1). Therefore, the model is accurately predicting real values, obtaining R^2 values close to 1 and where the *RMSE* value decreases, more than 30%. In addition, the data dispersion improved significantly, by approximately more than 50%, after the initial model calibration, indicating a clearer and more predictable relationship between them.

TABLE 1. Statistical measures of the comparison of results obtained in calculations with the use of original empirical model and improved empirical model of the total nitrogen load for rivers

Specification	Statistical measure	Modeling	Calibration and validation
Calibration 2005–2015	coefficient of determination (R^2)	0.81	0.81
	root mean square error (*RMSE*)	14 743.05	5 022.38
	standard deviation (*SD*)	21 281.05	11 534.44
	Nash–Suthcliffe's model efficiency coefficient (*NSE*)	–1.14	0.75
Validation 2016–2021	coefficient of determination (R^2)	0.82	0.82
	root mean square error (*RMSE*)	8 847.55	3 342.31
	standard deviation (*SD*)	12 440.31	6 742.71
	Nash–Suthcliffe's model efficiency coefficient (*NSE*)	–0.29	0.82

Source: own elaboration.

Similarly, the values calculated with the initial model, without calibration, show a negative Nash–Suthcliffe's model efficiency coefficient (*NSE*), implying that the model is not suitable for predicting observed data. However, through calibration, this coefficient shows us that the model has a good fit and a robust predictive capacity.

Based on Figure 4b, watersheds that present a percent-age close to 33–66% show a more concentrated distribution of nitrogen load data, i.e., there is less variability in these data, and the distribution is symmetrical. However, the calculated nitrogen load for watersheds with a high percentage of agriculture shows widely distributed data, indicating high variability in the data. Regarding the data calculated for watersheds with a low percentage of agricultural area, the distribution of nitrogen load is asymmetrical and even contains outliers. Therefore, the empiri-

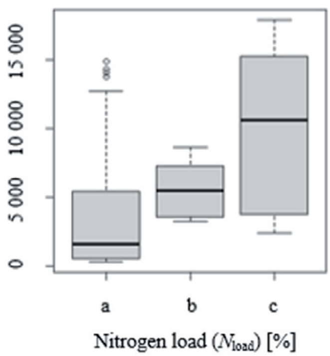

FIGURE 4. Distribution of nitrogen load (N_{load}) by percentage of agriculture: a – 0–33% of agriculture land; b – 33–66% of agriculture land; c – 66–100% of agriculture land

Source: own elaboration.

cal model fits the watersheds with an agriculture land ranging from the values already mentioned better.

The nitrogen load from observations and modeling for lakes is shown in Figure 5. The significant difference between the observed and modeled results indicates further development of the existing empirical models to accurately represent the studied area.

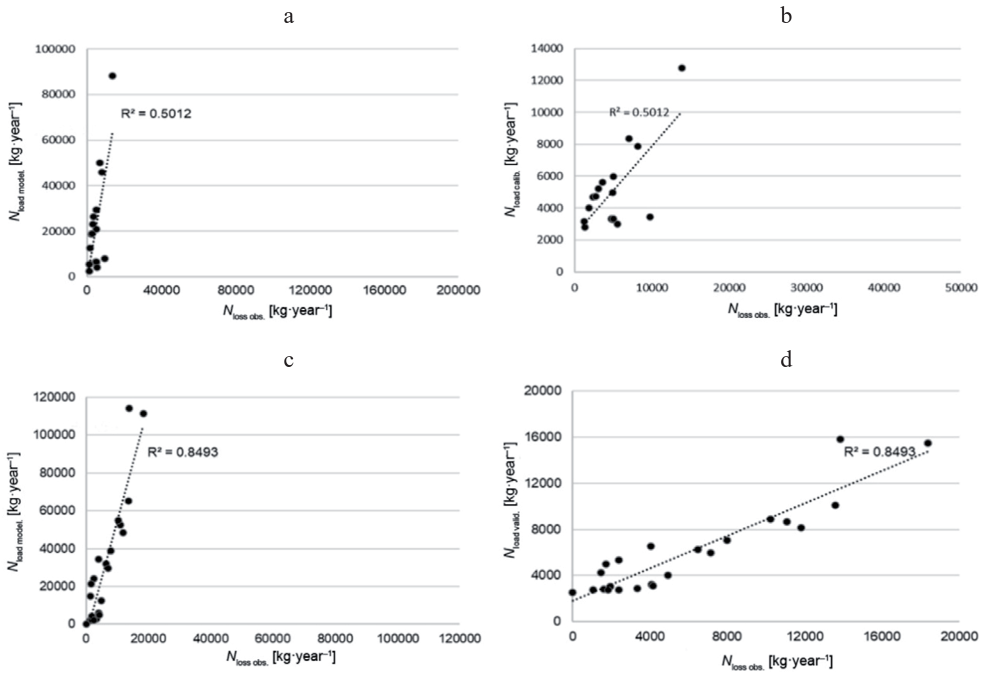

FIGURE 5. Linear regression of lakes monitoring points: a – nitrogen load observed ($N_{\text{load obs.}}$) and nitrogen load modeling ($N_{\text{load model.}}$) in 2008–2019; b – nitrogen load observed ($N_{\text{load obs.}}$) and nitrogen load calibrated ($N_{\text{load calib.}}$) in 2008–2019; c – nitrogen load observed ($N_{\text{load obs.}}$) and nitrogen load modeling ($N_{\text{load model.}}$) in 2020–2021; d – nitrogen load observed ($N_{\text{load obs.}}$) and nitrogen load validated ($N_{\text{load valid.}}$) in 2020–2021

Source: own elaboration.

The correlation between the observed and modeled nitrogen load is depicted in Figure 5a, with applied calibration (2008–2019) and validation (2020–2021). The results show that both graphs have the same R^2 value, which is 0.5012 and 0.8493, respectively. The correlation quality can be determined by examining the R^2 value and correlation line. Based on the graph, the R^2 value indicates comparable results between the two figures, but the correlation line shows that Figure 5b performs better than Figure 5a, which can be attributed to the utilization of a new empirical model. In addition, Figure 5b

TABLE 2. Statistical measures of the comparison of results obtained in calculations with the use of original empirical model and improved empirical model of the total nitrogen load for lakes

Specification	Statistical measures	Modeling	Calibration and validation
Calibration 2008–2019	coefficient of determination (R^2)	0.5012	0.5012
	root mean square error (*RMSE*)	25 668.16	2 256.76
	standard deviation (*SD*)	21 427.88	2 491.61
	Nash–Suthcliffe's model efficiency coefficient (*NSE*)	–64.34	0.5
Validation 2020–2021	coefficient of determination (R^2)	0.8493	0.8493
	root mean square error (*RMSE*)	36 483.58	2055
	standard deviation (*SD*)	32 191.68	3 743.22
	Nash–Suthcliffe's model efficiency coefficient (*NSE*)	–54.43	0.82

Source: own elaboration.

exhibits better results, other outcomes obtained from utilizing the newly calibrated and validated model are displayed in Figure 5d. Moreover, the Nash–Suthcliffe's values indicate a nitrogen load by the existing empirical model and observed for 2008–2019 and 2020–2021 is –64.34 and –54.43, respectively. While the new empirical model and observed is 0.5 for period 2008–2019 and 0.82 for 2020–2021, which are close to 1 that indicates the new empirical model has suitable results to the observed load.

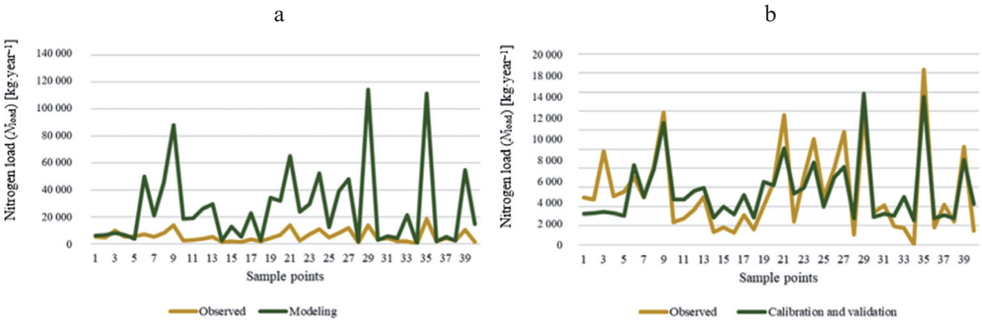

FIGURE 6. Sample points in the lake in 2008–2020: a – nitrogen load observed and modeling; b – nitrogen load observed, calibration, and validation

Source: own elaboration.

Figure 6a depicts the nitrogen load results through both observations and empirical models for each sample point within the lake. It is apparent that the calculated nitrogen load values from the empirical model are higher compared to the observation results. On the other hand, Figure 6b demonstrates outcomes from the same source, but it is compared to the results from the newly calibrated empirical model.

By using the new empirical model, the nitrogen results approach the observation results. This is further supported by the *RMSE* calculations in Table 2 which indicate the decreasing of the *RMSE* 92% for 2008–2019 and 95% decrease for 2020–2021 from the existing empirical model results. The determination of data approximation is assessed through the analysis of the R^2 and the *RMSE* values. According to Kutner, Nachtsheim, Neter and Li (2005), and Hair, Black, Babin, Anderson and Tatham (2019), that the coefficient of determination, or the R^2, is a commonly used matrix to assess the goodness of fit of a regression model to the data. Measures of the R^2 for the proportion of the variance in the dependent variable that can be explained by independent variables in the model, with values ranging from 0 to 1. The high value of the R^2 indicates a good fit of the model to the observed data, with more variance explained by the independent variables. Whereas it is important to consider the limitations or potential errors with the new equation when applied to lakes in the Biebrza catchment. The equation consistently yields results that are 1.3% lower than the actual values, which indicates a systematic discrepancy in the estimation.

Calibration and validation of the empirical model

Although the results of the original empirical equation showed values that follow a trend equal to those observed, the difference between them is huge. Therefore, it was necessary to calibrate said equation to adapt it to the conditions presented by the Biebrza catchment in rivers and lakes. For which, a linear regression was performed in RStudio and using the value of the intercept coefficient, the equation was adjusted. Resulting in the original equation divided by the established values in the case of the rivers.

$$N_{loss} = 1.124 \cdot \exp(-3.080 + 0.758 \cdot \ln(H) - 0.0030S + 0.0249D) / 1.845 + 70.38. \quad (3)$$

In addition, the results of the original equation for the lakes around Biebrza catchment need to be developed to approach the results of observation. Therefore, a better equation should be used in this case (Eq. 4):

$$N_{loss} = 1.124 \cdot \exp(-3.080 + 0.758 \cdot \ln(H) - 0.0030S + 0.0249D) / 8.6 + 2{,}541. \quad (4)$$

Likewise, these new equations were validated using the water quality data for the years 2016 to 2021 (Eq. 3) for rivers and 2020–2021 for lakes (Eq. 4). Obtaining values that fit better and with greater precision (Tables 1 and 2). It is important to emphasize that these values were not used for calibration.

Discussion

Agriculture is one of the factors contributing to nitrogen load in the Biebrza river watershed. Therefore, tools are needed to identify factors contributing to nitrogen load to establish sustainable guidelines for minimizing the nitrogen impact. Thus, the use of this empirical model will serve as a tool to implement guidelines that can be used by farmers in the surrounding areas and by authorities responsible for establishing agricultural policies in the area. Fertilizers play a crucial role in agriculture, but they have negative effects on the water bodies, such as eutrophication. Therefore, they should be applied considering optimal economic and environmental performance (Berger et al., 2020).

Based on the equation used (Eq. 1), the results calculated differ from the observation results. Consequently, a new equation that can be tailored to approach the total nitrogen derived from observations is necessary. According to Figures 3 and 5, the average nitrogen load from observed data is approx. 7,000 and approx. 5,000 kg·year^{-1}, while the existing model is approx. 13,000 kg·year^{-1} and approx. 26,000 kg·year^{-1} (Eq. 1), and the new empirical model is approx. 7,000 kg·year^{-1} and approx. 5,000 kg·year^{-1} (Eqs 3 and 4) for the river and lakes respectively. The nitrogen load from the existing empirical model (Eq. 1) has increased almost twice in the river and by five times in the lakes the actual result, while the new empirical model (Eqs 3 and 4) shows a difference of less than 4% from actual result. To establish the new equation, a linear regression analysis was used, which is a statistical technique that allows the analysis to model the relationship between a dependent variable and independent variables. Furthermore, it evaluates the strength of the association between the observed and modeling data. It assumes that the relationship between the variables can be described by a linear equation and seeks to find the best-fitting line summarizes this relationship (Aloui, Jammazi & Nguyen, 2014).

Nitrogen load calculations based on observations involve determining the catchment area for each sample, knowing the precipitation and runoff around the Biebrza watershed, and multiplication of these values by the nitrogen content in each observation. This leads to the calculation of nitrogen load in kilogram per year, which serves as a reference point for the observed data. On the other hand, nitrogen load calculations can be done using an equation (Eq. 1), which does not require direct field observations but only needs precipitation in the catchment area, runoff, and samples from the area. In the case of the rivers 11 sub-basins were used to modify the original empirical model (Eq. 3) to establish an equation that fits the conditions of the Biebrza area. Furthermore, the determination of data approximation is assessed through the analysis of R^2 and *RMSE* values. According to Kutner etal. (2005), and Hair et al. (2019), that the coefficient of determination, or the R^2, is a commonly used matrix to assess the goodness of fit of a regression model to the data. Measures of the R^2 for the proportion of the variance in the dependent variable that can be explained by independent variables in the model, with values ranging from 0 to 1. The high value of R^2 indicates a good fit of the model to the data, with more variance explained by the independent variables. To verify its efficiency, R^2 was first determined and showed no variation with respect to observed values compared to the modified model during the years 2005 to 2015. Validation performed for the following years, 2016 to 2021, showed an improvement in this value. Therefore, to ensure more accurate comparison between observed data, existing model, and new empirical model, an analysis using the Nash–Suthcliffe's coefficient which is a statistical measure of goodness-of-fit between observed and modeled values in hydrological and environmental modeling. It is calculated as the ratio of the sum of squared differences between observed and modeled values to the variance of the observed values. According to Nash and Sutcliffe (1970), as cited in Legates and McCabe Jr. (1999), defined the coefficient of efficiency which ranges from minus infinity to 1.0, with higher values indicating better agreement (Legates & McCabe Jr., 1999). In addition, the statistical values of the *RMSE*, and standard deviation show statistically acceptable results compared to the modified equation that fits better with the conditions of this basin, indicating that this model can be used to predict nitrogen load in the Biebrza river and for decision-making regarding the reduction of this nutrient.

The nitrogen from agricultural runoff is the main source of nutrient input into a river basin (Xia et al., 2020). Leading to environmental problems, in addition, the efficiency of nitrogen use in agriculture is very low and the load of this nutrient occurs mainly towards water bodies (Salvador-Castillo et al., 2021). Similarly, the accumulation of this type of nutrients leads to a process of eutrophication in water resources (Toro Gallego, 2019). Therefore, the agricultural percentage that covers a watershed is a primary factor in determining nitrogen load (Boyer, Goodale, Jaworski & Howarth, 2002). Thus, through the box plot (Fig. 3), it was observed that while the model works for the entire watershed, this model adapts better to sub-basins the agricultural percentage of which varies between 33% and 66%. That is, if stakeholders want to know the behavior of nitrogen load in the Biebrza river, applying this model (Eq. 3) will provide adequate data for decision-making in nitrogen reduction. However, more accurate and better-adjusted data to reality will be obtained if this equation is applied to those sub-basins which agricultural area covers the afore-mentioned range.

However, it is essential to note that although, based on statistical calculations, this model allows for fairly accurate prediction of nitrogen load, it has its limitations. Firstly, since it is based on historical water quality data, there are several gaps in different times of the year that prevent a more precise determination of nitrogen behavior during these times. Likewise, the accuracy of this model also depends on the quality and precision with which such samples were taken. During the analysis of water quality data, outliers were observed, which could be due to a specific event that caused an increase or decrease outside the range of all data, or to an inadequate sampling, as well as some sub-catchments not being sampled periodically, which prevented an analysis of those areas. The outlier values (Figs 3a and 3b) that use for calibration of the empirical model represent the highest value of each year (2005–2015) of Zelwianka (Zalewianka) – Mazurki sub-catchment. Therefore, these values were considered, when calibrating the empirical model. In addition, extreme weather conditions or unpredictable events that could affect nutrient load values were not considered. However, despite these limitations, this model can be used for the conditions of the Biebrza river, to make decisions to mitigate the amount of nitrogen affecting this watershed.

The calculation of nitrogen loss developed by (Naturstyrelsen, 2014) present in (Eq. 1) shows values that do not match with the nitrogen load observed. Hence, to be used for the conditions of the Biebrza basin and its lakes, the model was calibrated (Eqs 3 and 4) using a linear regression analysis. Once the new conditions were established, this new empirical model allowed to have more accurate and precise data compared to the original values. Therefore, the original empirical model presents a versatility that allows it to be adapted to the characteristics of various hydrographic basins. As is the case of the Ryck river in Germany, where this model was calibrated to meet the condition of this basin and it could be used as a key for the implementation of water buffer zones for the mitigation of the nutrient runoff (Trehan, Wichtmann & Grygoruk, 2022). Similarly, there are more complex models that forecast Nitrogen load, for instance Global NEWS, a Phyton framework and a global, multi-element and multi-form model of nutrient export by rivers (Mayorga et al., 2010), nonetheless, its application can become complicated if it is used by people who do not have the skills to apply the model in mentioned software.

Knowing the nitrogen load will allow determining the amount of fertilizer that should be applied to a crop will also help identify which sub-catchments are most affected, to minimize nitrogen load in the most affected areas. Fertilization aims to maximize yield using minimal fertilizer. There are different methods to determine this factor, ranging from recommendations to mathematical models that establish dosage and yield, using chemical analysis, climatic characteristics, and crop management techniques as the main information (Quiroga & Bono, 2012). Due to the high economic costs, chemical analysis can become a disadvantage when determining fertilization guidelines. Therefore, by applying the previously established model, the amount of nitrogen load can be calculated in a simple way.

The new proposed empirical model allows determining the Nitrogen load, adapted to the conditions of the Biebrza River basin. As well as showing the adaptability of the original model towards new basins.

Conclusions

The assessment of nitrogen in the Biebrza catchment for agriculture is the crucial issue. That is the reason why it is important to have information related to the inflow of nitrogen in the area, to mitigate pollution processes. This research presents that the existing model for nitrogen load shows significant results, however, in order to be applied in the Biebrza basin it needs to be developed into a more advanced empirical model. By the analysis regression and some statistical analysis, the prediction result of a new empirical model was given in the study case and it is more suitable with the nitrogen load observed. Nitrogen load for the existing model is approx. 13,000 kg·year^{-1} and approx. 26,000 kg·year^{-1}, whereas, by the new empirical model is approx. 7,000 kg·year^{-1} and approx. 5,000 kg·year^{-1} for rivers and lakes, respectively. Therefore, it can be used for future research in the Biebrza river or water bodies with similar characteristics, such as precipitation and agricultural land. However, it is important to note that if more accurate values with a lower range of error are desired, the model should be optimized for each sub-watershed, considering the respective factors that affect the Nitrogen load. Thus, this model can be used as a guide in decision-making regarding the management and protection of a river, such as establishing sustainable agricultural measures that prevent nitrogen load and enabling the establishment of public policies for the protection of water resources.

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Summary

Developing an empirical model for assessment of total nitrogen inflow to rivers and lakes in the Biebrza river watershed, Poland. Nitrogen load is crucial for its application in various fields such as agriculture and improving water quality control for authorities responsible for establishing agricultural policies in the area. The calculation of nitrogen load using existing equations is not applicable for all types of rivers, thus requiring the development of a new equation that can be applied to lakes and rivers in the Biebrza river catchment. To determine the new equation, extensive mapping of the catchment area was conducted, which was adjusted to precipitation and runoff in the area, allowing the observed results to be compared. Based on several analyses, the new equation has better accuracy, *RMSE* of the new model-based estimation decreased by 65.9% in 2005–2015 and 62.2% in 2016–2021 for river and 92% in 2008–2019 and 95% in 2020–2021 for lakes. Therefore, the application of the new calibrated empirical model provides results close to the real values and it can be used in the Biebrza river basin to simulate the total nitrogen runoff.

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Urban garden as a water reservoir in an urban area – a literature review

Keywords: meta-analysis, water retention indicators, community garden, soil maintenance, planting type

Introduction

In the 21st century, cities have become a place where the percentage of the world's population has become higher than that of non-urban areas. Thus, today cities have become the places where a sustainable living environment is more relevant (Brown, Keath & Wong, 2009). According to the United Nations projections, the world's population will continue to grow to around 8.5 billion in 2030 (United Nations Department of Economic and Social Affairs, Population Division [UN DESA], 2022), and two-thirds of the human population will already live in cities in 2025 (Russo, Escobedo, Cirella & Zerbe, 2017), of which 8 million will be in Europe and as many as 920 million in Asia (UN DESA, 2022). With traffic migration from rural to urban areas, there is a growing need for water conservation in the cities. Against the backdrop of the climate crisis, planners are

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trying to prepare a resilient environment by ensuring proper water management in urban spaces (Brown et al., 2009). According to Goal 6 of the SDGs, 25% of the population will be affected by drought and steppe formation in 2050. Therefore, researchers have called for actions related to infrastructure investments aimed at the protection and restoration of aquatic ecosystems, the improvement of water quality through the reduction of pollution, water efficiency through its efficient use, integrated resource management and the public participation of urban communities in the above actions (Barcena, Cimoli & Perez, 2018). One solution to this issue is the creation of green infrastructure that can act as a buffer zone in the city by using urban gardens for climate regulation, carbon capture, food security, educational opportunities on environmental issues and water retention (United States Environmental Protection Agency [US EPA], 2021; Tomatis, Egerer, Correa-Guimaraes & Navas-Gracia, 2023).

Urban gardening is defined as crops and livestock production in cities (Tomatis et al., 2023), but different scales of urban gardening must be considered. In Europe and Asia, these activities take many forms, such as allotment gardens, urban farms, community orchards (Lin, Philpott & Jha, 2015; Burchard-Dziubińska, 2020), community gardens (Lin et al., 2015; Burchard-Dziubińska, 2020; Menconi, Heland & Grohmann, 2020; Kingsley et al., 2021). The definition of the 'urban garden' (UG) thus includes many different forms of cultivation and land use, using nature-based solutions (Cabral, Costa, Weiland & Bonn, 2017). City gardens are variable in time and space, and they are easy to adapt and transform for the needs of specific groups of residents and environmental purposes. Governance by formal or neighborhood groups is easily supported by public institutions and local authorities (Menconi et al., 2020).

Asia's population quadrupled in the 20th century (Akaeze & Nandwani, 2020), and similarly to Europe, migration to cities directly contributes to the continent's urbanization (Hampwaye, 2013). Thus, urban expansion in Asia is concentrated in metropolitan areas. This population growth has resulted in a decrease in agricultural land due to conversion to other non-agricultural purposes (Akaeze & Nandwani, 2020). Moreover, it has led to decreased food availability and increased food prices (Zezza & Tasciotti, 2010). The crops grown mainly for personal use and sale in Asian cities are mostly edible. In particular, the development of urban agriculture in Asia faces several problems, such as low acreage of land or problems with land ownership and use, as well as planning constraints and, in addition, high prices, technological and infrastructural challenges related to the establishment, operation and management of such land (Van Tuijl, Hospers & Van Den Berg, 2018). Despite multiple problems, many countries and cities in Asia are prosperous in urban farming programs, for example, the Pune City Farming project, Mumbai, Delhi, as well as some programs established by numerous ventures to train and assist farmers (Akaeze & Nandwani, 2020).

The history of urban gardens – the allotment garden began in Europe in Germany (Kappeln) in 1814 (Cabral et al., 2017). Currently, there are over 2 million allotment gardens in Europe associated with the Office International du Coin de Terre et des Jardins Familiaux (http://jardins-familiaux.org). Allotment gardens can be found all over Europe, especially in Central and Northern Europe (Bell et al., 2016; Cabral et al., 2017). As green areas, they effectively complement the green infrastructure of the cities. The community garden, constituting a different form of an urban garden, has existed for 20 years as a supplement to allotment gardens that fill urban voids. These community gardens promote environmental education and social cohesion and contribute to climate adaptation. One of the triumphant histories of urban gardens is located in Lisbon, with several community gardens serving food provision, cultural services and educational opportunities, as well as enhancing green infrastructure by providing ecological corridors in urbanized areas, while in Leipzig accessibility is limited, and the garden is located on private land managed by an allotment organization. Many native species can be found in old allotment garden complexes because many plots are abandoned (Speak, Mizgajski & Borysiak, 2015; Borysiak, Mizgajski & Speak, 2017). In the popular discourse on urban gardening, there has been extensive research into the socio-economic benefits, contribution to promoting human health and well-being, and the potential to support social cohesion and spatial justice (Cabral et al., 2017; Gawryszewska, Łepkowski & Wilczyńska, 2019). However, more needs to be heard about the potential of urban gardening as a means of urban retention in the city, especially in the context of the climate crisis (Tomatis et al., 2023). Therefore, this study of contemporary literature aims to answer the following research questions:

- RQ1: Do contemporary scholars recognize the potential of urban gardening in improving urban retention?
- RQ2: What indicators have been found in the literature as crucial for enhancing urban retention? Do they form specific groups of factors?
- RQ3: Are there any disparities in the occurrence of indicators among continents?

Material and methods

Methods of material meta-analysis and data collection

Preliminary searches were conducted using peer-reviewed literature from various academic databases, including Web of Science (WoS), Science Direct (SD), Springer and MDPI – the search criteria aimed to collect papers related to urban agriculture and gardening. The search employed logic sentences using keywords, where 'OR' indicated either one or both terms and 'AND' indicated all the terms that should be present (Alberti, Bessa, Hardy, Trappman & Umney, 2018). In the identification phase, the search keywords used were 'urban garden' OR 'allotment garden' OR 'community garden', OR 'urban agriculture' combined with 'water retention'. After removing duplications, the total results obtained were as follows: Science Direct (n = 352), Springer (n = 95), MDPI (n = 25), and Web of Science (n = 875) – cf. Round 1 in Table 1.

TABLE 1. Preliminary meta-analysis of five popular academic databases

Round	WoS	SD	Springer	MDPI	Total
1	875	352	95	25	1347
2	3	211	6	0	220
3	2	144	6	0	202

Source: own elaboration.

The procedure described above made it possible to identify the recurring indicator words used by the authors: 'soil maintenance', 'rainwater/stormwater infrastructure', 'planting type', and 'watering system'. Finally, the four factors were used to refine the search. The refined results were as follows: Science Direct (n = 211), Springer (n = 6), MDPI (n = 0), and Web of Science (n = 3) – cf. Round 2 in Table 1. Green roofs were then excluded from the search to focus on ground-based urban gardens, resulting in the following results: Science Direct (n = 144), Springer (n = 6), MDPI (n = 0), and Web of Science (n = 2) – cf. Round 3 in Table 1.

After thoroughly reading the papers, only 46 were selected for further analysis considering their content relevance to the topic (Fig. 1).

Once a fine collection of literature was obtained, the next step involved filtering the retrieved results to create a binary-categorized matrix for analysis purposes.

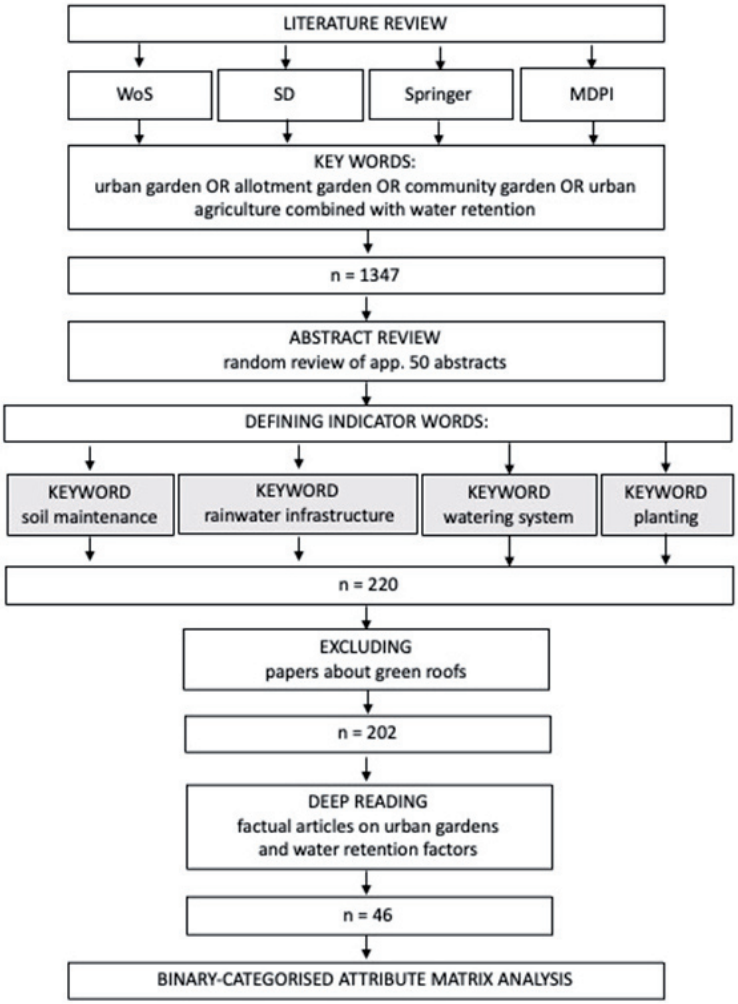

FIGURE 1. Schematic representation of the research procedure

Source: own eleboration.

Methods of data analysis

To obtain answers to our research questions, we did some follow-up work. The initial literature review was used not only to define the indicator keywords (RQ2), but also to understand the context and broader background of the formulations considered indicative. Furthermore, the clarified definitions served to further define them in detail in the subsequent stages of the meta-analysis. Both the number of articles and the case studies described in them were analyzed. Thus, the research phase ultimately helped to determine the perceived potential of urban gardening in improving urban retention by contemporary researchers (RQ1).

The data resulting from a meta-analysis in the form of an attribute matrix (binary-categorized) was further organized. The sets of attributes for the articles extracted using meta-analysis (Round 2 in Table 1) were also clustered using Ward's cluster analysis with the analytical tool R. This made it possible to identify the role of various indicators mentioned in the literature (RQ2). The number of case studies described per country and continent was determined (RQ3). The graphical representation of the dendrogram was developed with the help of the SRPLOT application available on the platform Bioinformatics.com.cn. The results were also visualized in tabular form using Microsoft Excel (version 16.56).

Water retention in urban gardens

The indicators for enhancing urban retention found in the literature

Authors show that urban gardens are dispersed in urban areas and can function more effectively than other types of green storm infrastructure (Chapman, Small & Shrestha, 2022; Ebissa & Desta, 2022). The built environment and, water-impermeable surfaces – paving, stone slabs and building roofs – increase surface runoff, contributing to uncontrolled flooding and water pollution (Miller et al., 2014). The function of stormwater retention and interception has therefore become an essential element of planning green areas in the city in order to mitigate the effects of accelerated surface runoff, especially in the event of extreme weather events resulting from climate change (Donat, Lowry, Alexander, O'Gorman & Maher, 2016; Pathak, Liu, Jato-Espino & Zevenbergen, 2017; Khurelbaatar et al., 2021; Yaduvanshi, Nikemelang, Bendapudi & New, 2021). Soil culture is also characteristic of urban gardens – rich in locally produced compost (Small et al., 2019). Characterized by porosity, they have a high-water retention capacity and evapotranspiration from garden plants grown in nutrient-rich soil (Qiu & Turner, 2013).

Although urban gardens use more water-to-water crops, seasonally observed evapotranspiration rates were almost twice as high as in areas covered with urban lawns (Saha, Trenholm, & Unruh, 2007; Monteiro, 2017). In addition, the literature claims that adding organic material can increase the water retention capacity (Young, Zanders, Lieberknecht & Fassman-Beck, 2014; Wadzuk, Hickman & Traver, 2015). Comparing the examined urban areas with different development – garden crops and urban lawns, the former, despite irrigation, were generally characterized by smaller leachates. Furthermore, Chapman's research suggests that urban gardens are more like stormwater green infrastructure, and rain gardens have outstanding water retention, infiltration and evapotranspiration capabilities regarding stormwater retention (Chapman et al., 2022). These benefits are noteworthy as urban gardens are built and maintained for other purposes, such as food production, recreation, decoration and other social benefits (McDougall, Kristiansen & Rader, 2019). Ecosystem services provided by city gardens cannot be overestimated.

A study by Chapman et al. (2022) confirms various features of urban gardens related to water retention, such as water retention and temperature reduction caused by evapotranspiration. They can provide benefits like specially designed green infrastructure. The importance of soil type in water retention in garden crops was disproportionate to the importance of the cultivated plant type (the difference between a lawn and a garden crop).

Precipitation characteristics (volume, intensity and time) and reference evapotranspiration dynamics are the most critical drivers of precipitation retention and runoff in different regions of the planet (Zhang et al., 2019). The efficiency of greenery retention in the city also depends on the properties of the substrate (De Ville, Le, Schmidt & Verbanck, 2017). Improving water storage in the soil is an important factor for healthy plant growth and subsequent yields. The authors say that short-term, high-density rainfall favored a reduction in runoff and thus increased water storage in the soil. Conversely, prolonged high-density rainfall favored reduced peak flow duration (Li, Li, Huang & Liu, 2020). The results of the study conducted by Chen, Ni, Shen, Xiang and Xu (2020) confirm that an urban garden with vegetable and fruit crops promotes the water retention effect and reduces surface runoff and peak flow duration. Types of crops and water flow in the soil can increase the water retention capacity of urban greenery, becoming an instrument of retention (Chen et al., 2020).

Regarding the literature analysis, four indicators of water retention were defined:
- soil maintenance/cultivation (using compost, mulching, perlite, etc.);
- rainwater/stormwater infrastructure (collecting rainwater water – special infrastructure);
- watering systems (system for providing water strait to plants);
- planting type (garden plants: flowers, vegetables, fruits, herbs on beds – no turf: lawn or turf with dicotyledonous plants).

Improving urban retention through urban gardening – analysis of resources of scientific literature databases

While working on the project, it became apparent that although the scientific literature covering the topic of water retention is abundant and the role of urban gardens recognized, the final number of articles on retention rates was not large. Of the 46 articles selected for the in-depth analysis, only 2 described all 4 indicators at once. Consecutively, 3 indicators were found in 5 papers, 2 in 12 and 1 in the 27 remaining papers. Regarding the occurrence of the individual indicators of retention, the indicator talking about soil maintenance and cultivation appeared in 30 papers, while the indicator on the type of planting appeared in 20. According to the authors, the predominance of these two indicators, specific to green spaces and gardens, demonstrates the vital role that urban gardens can play in a resilient urban environment. It seems to be particularly apparent in research about crop vegetation in urban gardens and agriculture (De Pascale, Dalla Costa, Vallone, Barbieri & Maggio, 2011; Reeves, Cheng, Kovach, Kleinhenz & Greval; 2014; Gregory, Leslie & Drinkwater, 2016).

On the other hand, the indicator for rainwater and stormwater harvesting infrastructure was found in 11 papers and for the watering system in 15. Here, we need to, following some authors (Gittleman, Farmer, Kremer & Mc Phearson, 2017; Kuehler, Hathaway & Tirpak, 2017; Peña, Rovira-Val & Mendoza, 2022), distinguish between rainwater and stormwater retention infrastructure. Then the issue under discussion becomes even less relevant in the results of our meta-analysis, although noted. To summarize this brief quantitative analysis, the authors are more willing to emphasize bioretention in urban gardens (Table 2).

TABLE 2. The representation of 4 defined indicators in in the final papers' set

Parameter	Soil maintenance and cultivation	Rainwater/stormwater infrastructure	Planting type	Watering systems
Indicators in total	30	11	20	15

Source own elaboration.

A dendrogram describing the grouping of the analyzed papers according to the attributes, which were the indicator attributes developed above, distinguished 2 main result groups. The first, comprising 14 papers, includes those in which we found only one indicator attribute, most often the one related to soil maintenance; in subsequent groups, this attribute is associated with further ones (Hatfield, Sauer & Prueger, 2001; Abdalla, Predotora, Gebauer & Buerkert, 2012). The next group is divided into three subgroups, containing 8 papers (articles related to the rainwater and stormwater infrastructure attribute (Amos, Rahman, Karim & Gathenya, 2018; Kopperlar, Marruglia & Rugani, 2021). Next 6 papers group articles containing soil maintenance and planting type (Chen et al., 2020; Chapman, Small & Shrestha, 2021) and the remaining 19 items, which is consistent with the number and distribution of attributes. Subsequent groups show further 'attaching' attributes. The final distribution divides the surveyed literature into 12 groups (Fig. 2).

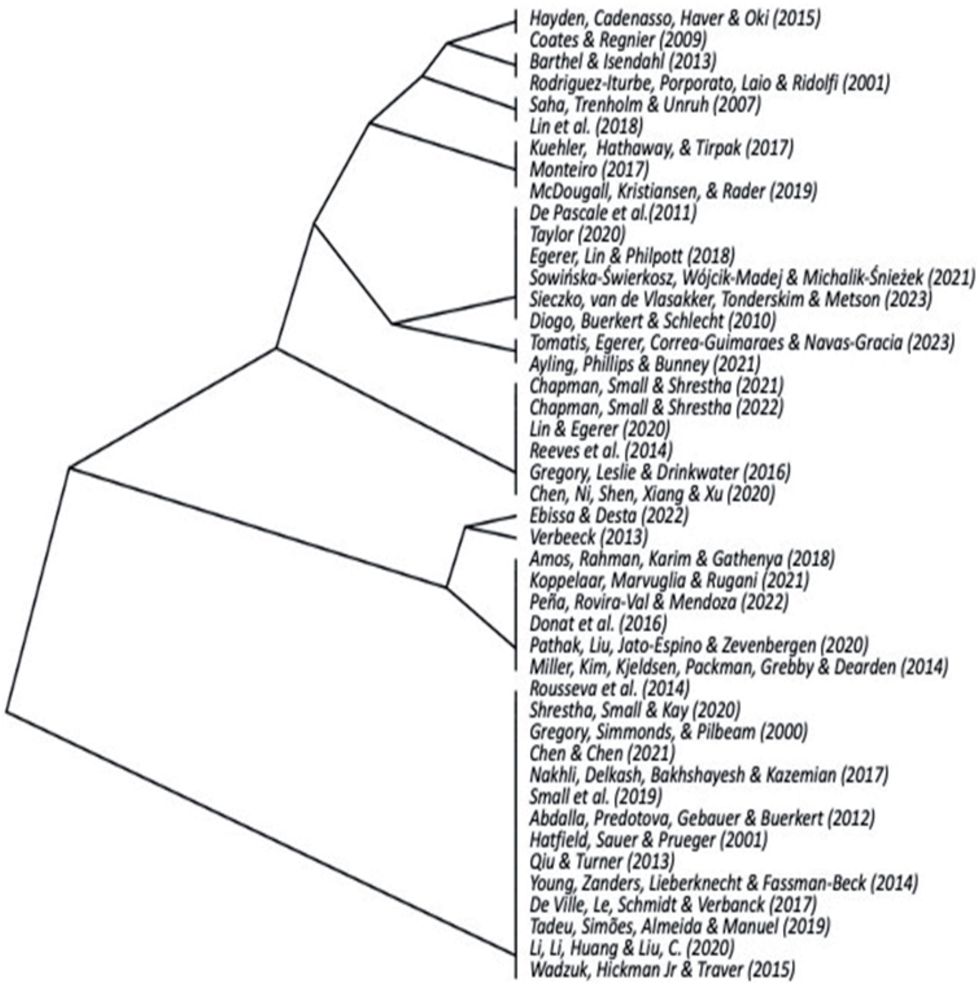

FIGURE 2. A dendrogram describing the grouping of the analyzed papers according to the attributes
Source: own elaboration.

Disparities in the indicators identified in the case studies between continents

Regarding case studies, there were 46 cases described in 39 from 46 analyzed papers. Most of the case studies cited (43.4%) were conducted in North America (Barthel & Isendahl, 2013), followed by Europe (28.3%) (Ayling, Phillips & Bunney, 2021), Asia, Australia and Oceania (8.7% each) and Africa (10.9%) in descending order. Significantly, there were no papers from South America (Fig. 3). Among the 46 articles describing cases in general there were 7 articles mentioning more than a case, including 2 within a continent (Rousseva et al., 2014; Nakhli, Delkash, Bakhshayesh & Kazemian, 2017) and 5 analyzing cases on two continents (Young et al., 2014; Egerer, Lin & Kendal, 2019; Gregory, Simmonds & Pilbeam, 2000; Koppelaar, Marvuglia & Rugani, 2021; Tomatis et al., 2023).

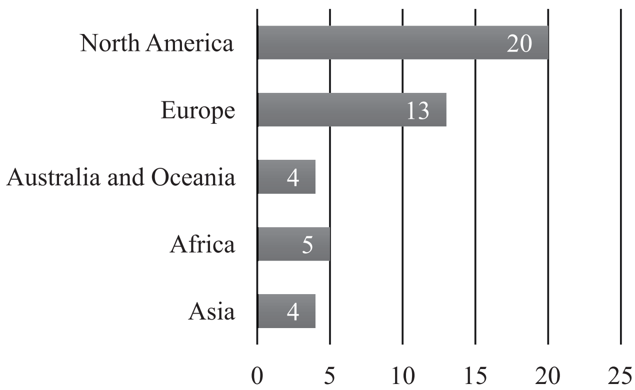

FIGURE 3. Distribution of the case studies on the continents
Source: own elaboration.

It is apparent that most cases from North America speak of indices related to soil maintenance and planting type, while indices from Europe are more evenly distributed. In contrast, it is difficult to speak of trends in the case of Asia, Africa (Diogo, Buerkert & Schlecht, 2010; Abdalla et al., 2012), and Australia and Oceania (Egerer et al., 2019; Li, Li, Huang & Liu, 2020), where the number of papers, and hence case studies described, could have been bigger. It may suggest a greater tradition of urban gardens and hence bioretention in Euro-American culture (Table 2).

Conclusions

The indicators to which we have devoted our meta-analysis of the scientific literature seem to initially summarize the most important aspects related to the scientific research carried out in this field. However, it would be worth conducting further studies, for example treating the threads related to the storm and rainwater infrastructure separately, compost and other additives to improve water retention in garden soil, as well as different types of planting and cultivation techniques. It could provide valuable guidance for urban gardeners, formulated at the scale of the garden rather than the whole city.

The most frequently mentioned indicator of an urban garden as a water reservoir is the use of compost and other additives by gardeners to improve water retention in the soil. Rainwater and stormwater harvesting infrastructure are only ranked second, usually mentioned in tandem with soil maintenance. Another indicator accompanying soil cultivation is the planting type, i.e., garden cultivation and its superiority over other types of greenery, which makes the urban garden unique among other bioretention areas.

The method adopted fulfilled its purpose, although a smaller than expected number of papers was obtained for a deep analysis. The research will undoubtedly continue, and we plan to add more keywords, e.g., sponge city and water resilient city, to broaden the number of results obtained. We also consider adding the scientific search engine Scopus and the ResearchGate and Academy portals. The latter will help to broaden research with grey literature. It will also help to reduce the risk of terminological differences possible between studies conducted on different continents.

The concept of the urban garden as a reservoir in water retention has been present in the scientific literature for years. Although observations have been made on a small sample, the North American literature, in particular, abounds with case studies summarizing the treatment of the urban garden as a retention tool in urban areas. Noticeable is the lack of representation of South America, if only because of its geographical proximity, which is worthy of more profound research. The paper can contribute to developing the first recommendations for urban gardeners and local authorities on the management and development of urban gardens, such as allotments and community gardens, considering their role as a retention tool.

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Summary

Urban garden as a water reservoir in an urban area – a literature review. The aim of the presented work was to show that contemporary researchers recognize the potential of urban gardening in improving urban retention, and that the contemporary scientific literature mentions specific problems-indicators of retention that can be useful for developing guidelines for authorities and gardeners on the management and development of urban gardens,

such as allotments and community gardens, considering their role as a retention tool. In this study, a meta-analysis of peer-reviewed scientific articles from popular scientific databases such as Web of Sciences, Science Direct, Springer and MDPI was performed, which was, besides literature analysis, the main method of research. Definitions of urban garden retention indicators were developed, which are: rainwater/stormwater infrastructure (collecting rainwater water – special infrastructure); watering systems (system for providing water strait to plants); planting type (garden plants: flowers, vegetables, fruits, herbs on beds – no turf: lawn or turf with dicotyledonous plants). The most frequent groups of indicators in the articles were also identified. The study also analyzed the distribution of surveyed articles between continents, noting the overrepresentation of articles from North America and the absence of articles from South America.

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Potential of a linear woodland landscape element as ecological corridor for carabid beetles (Coleoptera: Carabidae): a case study from Poland

Keywords: Carabidae, forest, ecological corridor, habitat connectivity, biological diversity, landscape management

Introduction

Fragmentation of landscapes and habitats has been identified as a main driver of biodiversity loss (Hanski, 2005; European Environmental Agency [EEA], 2011). Small habitat fragments can only support small populations, which are more vulnerable to extinction (Millennium Ecosystem Assessment [MEA], 2005). Species with a low dispersal power are especially endangered because for many species which are unable to fly, the transfer between suitable habitats may be hampered or even impossible and population extinctions cannot be compensated by refoundings (den Boer, 1990). Forests are among those habitat types which are especially threatened by fragmentation (Millennium Ecosystem Assessment, 2005). A solution to counteract the problem of landscape fragmentation are the so-called ecological corridors,

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i.e. linear landscape elements, which connect individual habitat patches (Soulé & Gilpin, 1991). Ecological corridors belong to measures, which support the conservation of biota in fragmented landscapes due to enhanced habitat connectivity (Bennett & Saunders, 2010) and can be planned and established on different spatial levels (Ćurčić & Đurđić, 2013). Other ecological benefits from such structures have been reported, like their capability as seed sources or contribution in limiting soil loss due to wind and water erosion (Ćurčić & Đurđić, 2013). Recently, ecological corridors have also been viewed from the perspective of being important means to achieve regional sustainable development (Shi et al., 2018). For example, in cities the green infrastructure, including ecological corridors, is being increasingly promoted as part of the broader sustainability agenda (Norton, Evans & Warren, 2016).

Studies on the function of linear landscape elements as ecological corridors have been carried out, amongst others, on linear grassland strips as corridors for butterflies (Öckinger & Smith, 2008), secondary forests as corridors for small mammals (Pardini, de Souza, Braga-Neto & Metzger, 2005), woody sites along rivers, railways and roads as corridors for garden shrews (Vergnes, Kerbiriou & Clergeau, 2013), hedgerows and roadside verges as corridors for carabid beetles (Eversham & Telfer, 1994; Vermeulen, 1994; Plat, Kuivenhoven & van Dijk, 1995) and railway edges for plants, Orthoptera and snails (Pujols & Panone, 2013). The studies demonstrate that linear elements may serve as corridors and buffer habitat fragmentation, but the effectivity is influenced by diverse factors, such as for example vegetation characteristics and corridor length.

Hence, in order to plan and establish such corridors successfully, we must understand the factors crucial for their effectiveness. Aiming to improve our knowledge in this regard, we initiated a study on a selected linear landscape element along a railway line using carabid beetles as indicators. Railways are important linear elements crossing different habitat types in the landscape. Their vegetated edges can play a positive role as ecological corridors, especially where the respective green areas are scarce (Pujols & Panone, 2013). Carabid beetles are suitable indicators for the quality of linear landscape elements as ecological corridors, because they are known to react to landscape-level phenomena (Koivula, 2011) and many species characteristic for woodlands and forests are unable to fly. Because their dispersal ability is restricted to walking activity, these species are particularly useful for assessing the effectivity of ecological corridors. Moreover, carabids are useful model organisms, so that they can give insights on the responses of other organisms to ecological corridors. Knowledge about the relationships between its characteristics and functionality as an ecological corridor is fundamental for successful planning. Therefore, the selected landscape element was described by several parameters, including both spatial characteristics and ecological indicator values. Potential habitats located at both ends of the study area have been investigated regarding their carabid beetle fauna in earlier studies (Błaszkiewicz & Schwerk, 2013; Schwerk & Dymitryszyn, 2015, 2017) which provided the possibility of a more complex assessment of apparent species migrations.

The aim of our study was to analyze the potential of the selected linear woodland landscape element in detail as ecological corridor for carabid beetles. We wanted to study if (1) the study area has potential as ecological corridor for some forest species, and (2) which environmental factors are of major importance for the occurrence of carabid beetle species in the linear landscape element. The results of the study are discussed from the perspective of designing ecological corridors as elements of landscapes.

Material and methods

Study area and field methods

The study area was an about 650 m long woodland strip of a width between about 15 and about 70 m along a railway line located in the Wałecki district in the West of Poland (Fig. 1). The strip is bordered to the North and the South mainly by agricultural fields. In the West it is connected to a pine forest with an age of about 49 years in 2020. In the East a patch of young trees, an older forest patch and a property with a cluster of tress, among them a couple of old fruit trees, are located.

Eight sampling plots were installed: the first sampling plot (sampling plot 1) was located in the pine forest in the West of the woodland strip, the second sampling plot (sampling plot 2) was located close to the border of the pine forest in the center of the woodland strip about 120 m to the West from the first plot, and sampling plots 3–8 were located in the center of the woodland strip at distances of about 90 m from each other to the East (Fig. 1).

Based on a value of 0 m for sampling plot 1, for each sampling plot the distance from this plot to the East was measured. At sampling plots 2–8 the width of the woodland strip was measured. For sampling plot 1 an "effective" width of 200 m was defined as based on information about movement distances and home ranges of big sized carabid beetles (Riecken & Raths, 1996; Skłodowski, 1999).

At each sampling plot an area of 25 × 25 m was marked in order to elaborate a phytosociological survey, with exception of sampling plot 3, where an area of 14 × 15 m was studied. The surveys were elaborated in the second week of July 2019 by recording the species and describing their occurrence using the cover-abundance scale of Braun-Blanquet (1964).

For each phytosociological survey the values of coverage of the plant species were transformed to a value of mean percentage cover according to Braun-Blanquet (1964): ±0.1%, 1 – 5%, 2 – 17.5%, 3 – 37.5%, 4 – 62.5%, and 5 – 87.5%. Next, for each sampling plot ecological indicator values of vascular plants were calculated, according to Zarzycki et al. (2002). The ecological values according to Zarzycki are a modification of the method of ecological values of vascular plants according to Ellenberg (1974) adapted to the conditions of the Polish climate. Ecological indicator values for light, temperature, soil moisture, trophy (fertility), soil acidity (pH), soil granulometric composition, and organic matter content (humus) were calculated as an average value.

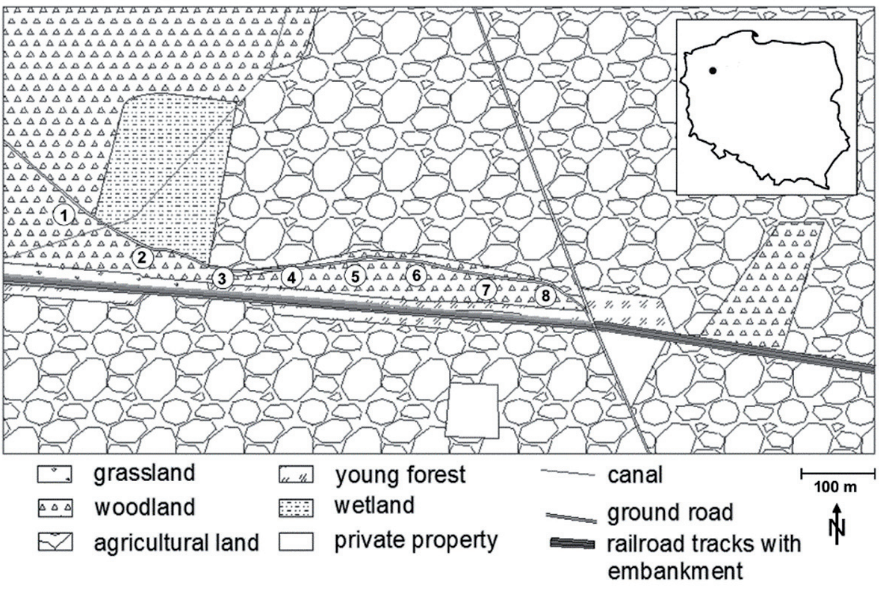

FIGURE 1. Map showing the location of the study area and the surrounding landscape. The small figure in the upper right indicates the location of the study area in Poland

Source: own elaboration.

Carabids were collected using pitfall traps (Barber, 1931). At each sampling plot three traps were installed about three m apart from each other. Traps were glass jars topped with a funnel (upper diameter of about 10 cm) set flush with the soil surface. A roof was suspended a few cm above the funnel and ethylene glycol was used as a killing agent and preservative. Carabids were sampled in 2019 from 02.06.2019 to 14.09.2019, with a replacement of the traps on 26.07.2019. Thus, carabid samples were taken two times during the whole collection period. Determination and nomenclature of the individuals collected was carried out according to Freude et al. (2004).

Statistical methods

For each sampling plot the catches of the three traps were pooled. For each species, the total number of individuals per sampling plot and the dominance value (percentage share of the individuals of the respective species on the total number of individuals collected at the sampling plot) were calculated. The characteristic forest species among the recorded species were identified based on literature (Larsson, 1939; Lindroth, 1945; Burakowski, Mroczkowski & Stefańska, 1973; Burakowski, Mroczkowski & Stefańska, 1974; Lindroth, 1986; Hurka, 1996; Freude, Harde, Lohse & Klausnitzer, 2004).

Correlations between selected parameters and selected species of the carabid fauna (forest species with low dispersal power of the tribes Carabinae and Cychrini and species collected with more than 50 individuals) and environmental parameters of the sampling plots were tested using Spearman rank correlation with IBM SPSS Statistics ver. 25.0.0.1.

In order to test the significance of the impact of the individual environmental variables on the whole species data set, we carried out a constraint ordination using CANOCO for Windows ver. 4.56 (ter Braak & Šmilauer, 2002). DCCA was first used to select the appropriate statistical model based on the longest gradient (Lepš & Šmilauer, 2003) and then redundancy analysis (RDA) with the Monte Carlo permutation tests (unrestricted, 1999 permutations) was carried out, first for each variable separately and then using automatic forward selection of variables (reduced model). The analysis was performed using inter-species correlations and dividing by standard deviation and unweighted data for each of the species. Because dominance values were used, the data were not transformed. CanoDraw for Windows ver. 4.14 was used to create a triplot with species fit range adjusted in such a manner that the 10 species with the highest fit into the ordination space were displayed (ter Braak & Šmilauer, 2002).

Results and discussion

Characterization of the sampling plots

The width of the woodland strip (sampling plots 2–8) varied between 14 m (sampling plot 3) and 70 m (sampling plot 6). Regarding the ecological indicator values, only rather slight differences between the sampling plots could be detected. The sampling plot in the forest (sampling plot 1) showed higher values compared to the sampling plots in the woodland strip (sampling plots 2–8) for soil moisture, trophy, soil acidity and organic matter content (Table 1).

TABLE 1. Characterization of the sampling plots by distance from sampling plot 1, width, and ecological indicator values according to Zarzycki et al. (2002) for light, temperature, soil moisture, trophy, soil acidity, soil granulometric composition, and organic matter

Parameter	Sampling plot							
	1	2	3	4	5	6	7	8
Distance [m]	0	115	232	327	421	511	605	698
Width [m]	200	64	14	38	66	70	53	40
Light	3.219	3.750	3.886	3.154	3.500	3.235	3.542	3.750
Temperature	3.594	3.542	3.477	3.000	3.529	3.294	3.500	3.542
Soil moisture	3.281	3.042	3.023	2.462	3.147	2.971	3.000	3.042
Trophy	3.656	3.000	3.136	2.462	3.294	3.206	3.375	3.000
Soil acidity	3.813	3.333	3.636	2.808	3.647	3.441	3.750	3.333
Soil granulometric composition	3.625	3.542	3.636	3.038	3.529	3.500	3.708	3.542
Organic matter	2.031	1.917	1.932	1.692	1.941	1.824	1.958	1.917

Source: own elaboration.

Carabid beetle inventory

Altogether, 1,646 individuals of carabid beetles, belonging to 39 species, were collected (Table 2). Among them the species *Amara communis* outstood with 1,170 individuals. The numbers of individuals collected at the sampling plots ranged from 72 (sampling plot 4) to 418 (sampling plot 7), with a very high share of individuals from species characteristic for forests at sampling plot 1 (Fig. 2a). The numbers of species collected at the individual sampling plots ranged from 9 (sampling plot 4) to 22 (sampling plot 7). Particular high numbers of forest species were collected at sampling plot 1 (14 species) and sampling plot 7 (13 species), the lowest number of forest species was collected at sampling plot 3 (2 species) – Figure 2b.

TABLE 2. Numbers of carabid beetles collected at the sampling plots

Species	Sampling plot							
	1	2	3	4	5	6	7	8
Agonum gracilipes			1					
Amara brunnea				1	3	3	17	4
Amara communis	3	109	41	34	235	316	293	139
Amara lunicollis							1	
Amara plebeja		1				1		
Amara similata		1	3	1	1	1	1	
Badister bullatus				1	1		1	
Badister lacertosus	4				1	2	2	1
Calathus cinctus						1		
Calathus fuscipes			1	2		2	2	2
Calathus melanocephalus						1	1	
Calathus micropterus			2	12	6		16	1
Calathus rotundicollis							2	
Carabus coriaceus	1					1		
Carabus hortensis	3				1		1	
Carabus nemoralis	3	1			1	5	6	
Cychrus caraboides	4							
Harpalus froelichii			1					
Harpalus laevipes	1	1					2	
Harpalus latus	9	4	1		3	7	3	2
Harpalus rubripes			1					
Harpalus rufipes			39	10	1	7	4	4
Harpalus tardus	1	1						
Leistus ferrugineus					1			
Leistus rufomarginatus	9					1	3	
Leistus terminatus	1	1						
Licinus depressus			4				3	1
Limodromus assimilis	1							
Nebria brevicollis							1	
Notiophilus biguttatus	1							
Notiophilus palustris	3	1			2	4	35	1
Panagaeus bipustulatus			1		1			1
Pterostichus melanarius	1							1
Pterostichus niger	13	6	11	6	21	3	2	5
Pterostichus oblongopunctatus	14	1		5	12	7	20	10
Pterostichus strenuus	9				1	1	2	
Stenolophus teutonus			1					
Synuchus vivalis						2		1
Zabrus tenebrioides		1	1					
Number of individuals	81	128	108	72	291	365	418	173
Number of species	18	12	14	9	16	18	22	14

Source: own elaboration.

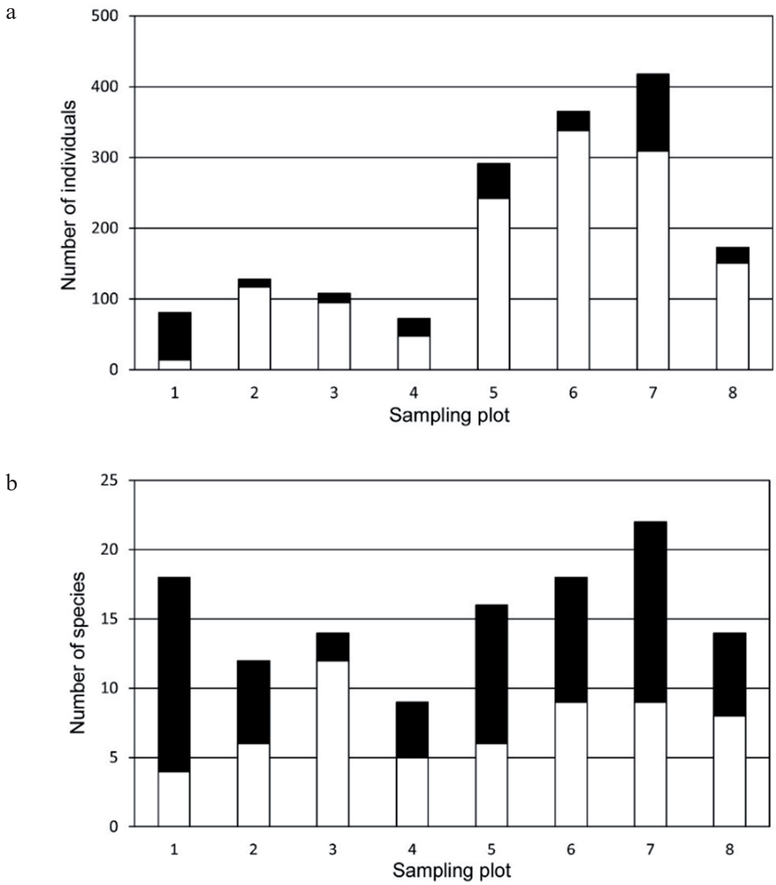

FIGURE 2. Numbers of individuals (a) and species (b) of carabid beetles collected at the sampling plots. Black parts of the bars indicate the share of forest characteristic individuals and species

Source: own elaboration.

Four characteristic forest species of the Carabinae and Cychrini tribes (*Carabus coriaceus*, *Carabus hortensis*, *Carabus nemoralis*, *Cychrus caraboides*) were collected. All of them were collected in the forest site (sampling plot 1). The three *Carabus* species were collected also in the woodland strip. However, only *Carabus nemoralis* was collected there regularly (at four of the seven sampling plots). Another big sized species with low dispersal power, *Pterostichus niger*, was collected at all sampling plots. Regarding other species (collected with more than 50 individuals), the forest species *Pterostichus oblongopunctatus* was collected at the forest site (sampling plot 1) and also regularly in the woodland strip (sampling plots 2, 4–8). Two non-forest species were collected with more than 50 individuals. *Amara communis* was collected at all sampling plots, but in much higher numbers at the sampling plots in the woodland strip (sampling plots 2–8) than at the forest site (sampling plot 1). *Harpalus rufipes* was collected only in the woodland strip at sampling plots 3–8 (see Table 2).

Number of species, number of forest species, number of forest individuals, *Carabus hortensis*, *Carabus nemoralis*, the sum of individuals from *Carabus* and *Cychrus* and *Pterostichus oblongopunctatus* showed a significant positive correlation with trophy. Except for *Carabus nemoralis* and *Pterostichus oblongopunctatus*, they were also significantly positively correlated with soil acidity, and *Carabus hortensis* was also significantly positively correlated with soil organic matter. Number of forest species, *Carabus coriaceus* and the sum of individuals from *Carabus* and *Cychrus* showed a significant positive correlation with the width of the sampling plots. *Amara communis*, however, showed a significant positive correlation with the distance from the forest site (sampling plot 1) and *Harpalus rufipes* was significantly negatively correlated with temperature and soil moisture (Table 3).

TABLE 3. Spearman rank correlation coefficients (r) and significance values (p) for correlations between selected parameters and selected species of the carabid fauna and environmental parameters of the sampling plots (statistically significant values are printed bold)

Species	r/p	Distribution	Width	Light	Temperature	Moisture	Trophy	pH	Granulation	Organic matter
Species	r	0.265	0.566	–0.115	0.176	0.176	**0.903**	**0.830**	0.467	0.648
	p	0.526	0.143	0.786	0.677	0.677	**0.002**	**0.011**	0.244	0.082
Individuals	r	0.690	0.262	0.252	–0.036	–0.084	0.395	0.299	0.204	0.180
	p	0.058	0.531	0.548	0.933	0.844	0.333	0.471	0.629	0.670
Forest species	r	0.024	**0.814**	–0.398	0.494	0.470	**0.855**	**0.759**	0.253	0.687
	p	0.955	**0.014**	0.329	0.213	0.240	**0.007**	**0.029**	0.545	0.060
Forest individuals	r	0.214	0.500	–0.551	0.048	0.096	**0.790**	**0.710**	0.192	0.575
	p	0.610	0.207	0.157	0.910	0.821	**0.020**	**0.045**	0.649	0.136
Carabus coriaceus	r	–0.252	**0.756**	–0.507	0.127	0.127	0.507	0.380	–0.127	0.127
	p	0.547	**0.030**	0.200	0.765	0.765	0.200	0.353	0.765	0.765
Carabus hortensis	r	–0.192	0.577	–0.346	0.484	0.581	**0.871**	**0.871**	0.401	**0.871**
	p	0.648	0.134	0.402	0.224	0.131	**0.005**	**0.005**	0.325	**0.005**
Carabus nemoralis	r	0.086	0.700	–0.266	0.117	0.031	**0.747**	0.624	0.266	0.438
	p	0.840	0.053	0.525	0.782	0.942	**0.033**	0.098	0.525	0.277
Cychrus caraboides	r	–0.577	0.577	–0.415	0.581	0.581	0.581	0.581	0.249	0.581
	p	0.134	0.134	0.307	0.131	0.131	0.131	0.131	0.552	0.131
Carabus + *Cychrus*	r	–0.146	**0.830**	–0.393	0.344	0.319	**0.884**	**0.785**	0.295	0.638
	p	0.729	**0.011**	0.336	0.405	0.441	**0.004**	**0.021**	0.479	0.089

TABLE 3 (cont.)

Species	*r*/*p*	Distribution	Width	Light	Temperature	Moisture	Trophy	pH	Granulation	Organic matter
Pterostichus niger	*r*	–0.647	0.156	–0.090	0.319	0.645	0.151	0.247	–0.090	0.331
	p	0.083	0.731	0.831	0.441	0.084	0.722	0.555	0.831	0.423
Pterostichus oblongopunctatus	*r*	0.333	0.524	–0.371	0.371	0.323	**0.731**	0.659	0.275	0.635
	p	0.420	0.183	0.365	0.365	0.435	**0.040**	0.076	0.509	0.091
Amara communis	*r*	**0.738**	0.190	0.180	–0.252	–0.275	0.180	0060	–0.060	–0.108
	p	**0.037**	0.651	0.670	0.548	0.509	0.670	0.888	0.888	0.799
Harpalus rufipes	*r*	0.313	–0.699	0.085	**–0.849**	**–0.764**	–0.400	–0.352	–0.145	–0.497
	p	0.450	0.054	0.842	**0.008**	**0.027**	0.326	0.393	0.731	0.210

Source: own elaboration.

None of the environmental parameters showed a significant impact on the formation of the total carabid assemblages (both when tested separately and using forward selection). However, the most important factors were "width" and "distance" when tested separately and "width" when using forward selection (Table 4).

TABLE 4. Results of the Monte Carlo permutation tests of the environmental variables tested separately and using automatic forward selection of variables (reduced model). During forward selection of variables "Trophy" and "Soil granulometric composition" were not added to the model due to collinearity. Lambda-1 – variance explained by the environmental variables separately; Lambda-A – additional variance explained when included in the model using forward selection

Variable	Tested separately			Forward selection		
	Lambda-1	*F*	*p*	Lambda-A	*F*	*p*
Width	0.34	3.14	0.124	0.34	3.14	0.124
Distance	0.34	3.10	0.095	0.17	1.66	0.221
Trophy	0.11	0.71	0.451	–	–	–
Light	0.10	0.67	0.479	0.03	0.00	1.000
Organic matter	0.09	0.57	0.507	0.12	0.44	0.329
Soil acidity	0.07	0.43	0.585	0.16	6.50	0.169
Soil moisture	0.06	0.37	0.628	0.05	0.44	0.590
Temperature	0.04	0.23	0.759	0.13	1.37	0.367
Soil granulometric composition	0.03	0.17	0.803	–	–	–

Source: own elaboration.

The first two RDA axes explained 95.6% of the total variance. The ordination diagram separated sampling plot 1 (forest site) from the other sampling plots along the first ordination axis and also sampling plots P3 and P4 along the second ordination axis. These were the sampling plots with a low width of the corridor. The factor with the highest impact was "width" which (together with most other factors) points towards sampling plot 1 (forest site). The "light" factor was negatively correlated with "width". "Distance", however, pointed in the opposite direction from sampling plot 1 along the first ordination axis. Characteristic forest species (e.g. *Carabus hortensis*) were located close to sampling plot 1 (forest site) in the diagram, species characteristic for open areas (*Amara similata*, *Harpalus rufipes*) were located close to sampling plot 3, and *Amara communis* was correlated with "distance" (Fig. 3).

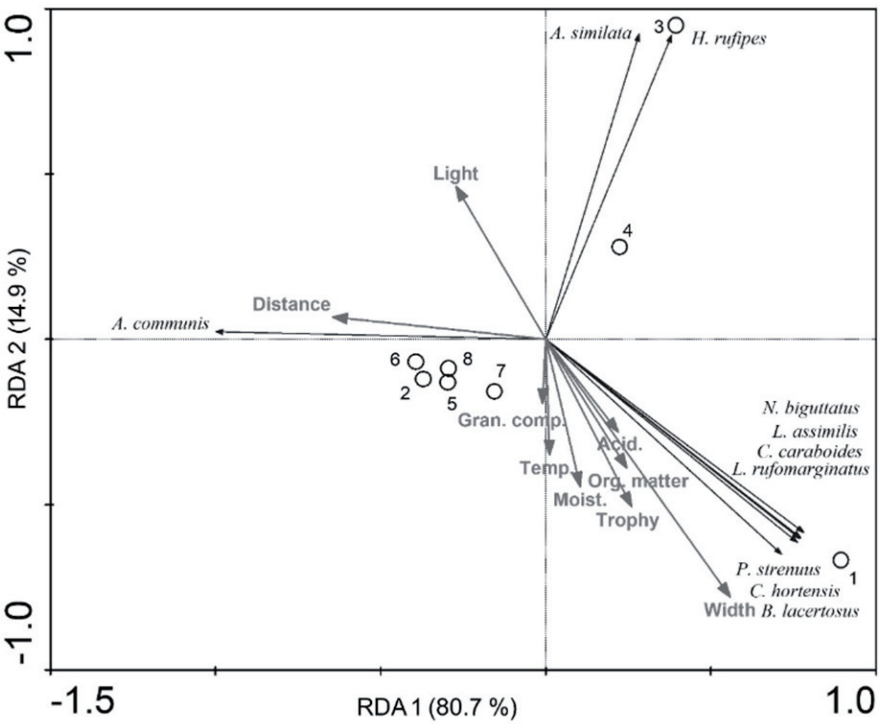

FIGURE 3. Ordination plot based on redundancy analysis (RDA) of the results for sampling plots (open circles) and species (thin arrows) and environmental variables (strong arrows). All species were included in the analysis, but only 10 species with the highest fit into the ordination space are displayed

Source: own elaboration.

Potential corridor function of the study site

The studied area indicated potential as an ecological corridor what is corroborated by data on the carabid fauna of adjacent habitats. The carabid fauna in the forest located west of the woodland strip has already been studied by Błaszkiewicz and

Schwerk (2013) and Schwerk and Dymitryszyn (2017), showing that with exception of *Cychrus caraboides* the forest species of the tribes Carabinae and Cychrini and also *Pterostichus niger* and *Pterostichus oblongopunctatus* were detected in this forest in earlier years, even if not all species in every year. As additional forest species of these tribes *Carabus violaceus* was proven. Schwerk and Dymitryszyn (2015) detected *Carabus nemoralis* and *Pterostichus niger*, both forest species unable to fly, in the insulated habitat located close to the East of the studied area (private property, see Fig. 1). These results underline that the woodland strip has a potential as an ecological corridor for some of the forest species with low dispersal power, though particularly for more eurytopic species (i.e. species able to tolerate wider ranges of ecological conditions), such as *Carabus nemoralis* and *Pterostichus niger*. An effectivity of linear landscape elements as corridors for these two species was shown by Gruttke, Kornacker and Willecke (1998), who studied a newly created habitat strip of hedge like plantations.

The results indicate that spatial (landscape) factors, i.e. the physiognomy of the corridor, are of higher importance than habitat parameters at the individual sampling plots for the formation of the carabid assemblages. However, individual species showed significant relations to the habitat parameters at the sampling plots. This indicates that both aspects are important for a proper functioning of a woodland strip as the ecological corridor. Plat et al. (1995), who studied the suitability of hedgerows as corridors for forest carabid species, concluded that the hedgerows should be as wide as possible. They should have a vegetation similar to the adjacent forest, thus being at least partly a potential habitat for target species. According to Soulé and Gilpin (1991), the effectivity of ecological corridors depends on the degree of edge effects, linearity and shape of the corridor. Shi et al. (2018) emphasize that the function of railways and expressways for connecting natural areas depends significantly on the width of undisturbed native vegetation along the verge.

However, linear woodland elements as ecological corridors for forest species might cause a barrier effect on species moving perpendicular to the respective corridor. Therefore, the idea of semi-open corridors was discussed (Eggers et al., 2009). Even if not statistically significant, *Harpalus rufipes*, a species characteristic for open areas, occurred in our study most frequently in the narrow part of the woodland strip (sampling plots 3 and 4), indicating that the varying width of the corridor is an important factor. The narrow parts seem to be permeable for at least some species of open habitats. In this part of the woodland strip no species from the tribes Carabinae and Cychrini were collected. However, the occurrence of species as *Carabus coriaceus* and *Carabus hortensis* at the sampling plots in the woodland strip more distant from the forest indicates that the narrow part does not hinder migration of these species along the strip. These two species are strongly connected to forest habitats and it can be excluded to a very high degree that they entered the respective parts of the woodland strip from the agricultural fields.

The results of our study provide some pieces of information regarding the rules for the construction of woodland strips as corridors for carabid beetles. Short narrow parts seem not to hinder migration through the corridor, but to enable permeability for species of neighboring habitats and higher soil trophy (fertility) and pH seem to be beneficial for some species. We assume that some of these rules also apply to other taxonomic groups of invertebrates. However, in order to guarantee the functionality as ecological corridor technical aspects have to be considered, too. Pujols and Panone (2013) raise the issue of construction solutions for overpasses, because they may interrupt some biological fluxes.

Today, ecological corridors have to also fulfil targets of sustainable regional development. Ćurčić and Đurđić (2013) recommend a set of strategies concerning this matter when implementing ecological corridors. Besides benefits related to species conservation this set also includes aspects concerning relationships in the local community, human resources and education. This implies that another important aspect involves the maintaining of such areas. Pujols and Panone (2013) formulated management and maintenance goals for railway vegetation, including the use of mechanical techniques and herbicides as well as the handling of invasive species. They conclude that long-term strategic plans incorporating economical, sustainable and multi-year integrated approaches for vegetation management are necessary. Villemey et al. (2018) identified a lack in studies dealing with the influence of management or surrounding landscape on insect dispersal along infrastructure verges. We conclude that studies towards this research direction are necessary to improve the strategies for constructing and using such landscape elements as ecological corridors.

Conclusions

The paper provided a case study regarding the potential of a linear woodland landscape element as ecological corridor for carabid beetles. The following conclusions can be outlined:

- The research area provides appropriate conditions which facilitate the migration of species from one habitat to another.
- The results indicate that spatial (landscape) factors, i.e. the physiognomy of the corridor (e.g. width, length), are more important than habitat parameters.

– The study indicates that the value of an individual site for biodiversity conservation should be assessed in the context of the landscape in which it is embedded. It is necessary to identify the kind of landscape features that are missing in order to exploit its full potential.
– Not only the individual elements of the landscape are important, but also its structure.

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Summary

Potential of a linear woodland landscape element as ecological corridor for carabid beetles (Coleoptera: Carabidae): a case study from Poland. Fragmentation of landscapes and habitats has been identified as the main driver of biodiversity loss. Ecological corridors may support the conservation of biota in fragmented landscapes due to enhanced habitat connectivity. We conducted a study in order to assess the potential of a linear woodland landscape element along a railway line as ecological corridor using carabid beetles as indicators. The results showed that for some forest species the studied woodland strip has potential as an ecological corridor. Trophy and soil acidity were most often significantly correlated with parameters and species, but width of the woodland strip and distance from the forest site were of highest importance for the formation of the whole carabid assemblages. The results of our study provide with information regarding rules for the construction of woodland strips as ecological corridors. Management strategies should integrate such areas in concepts of sustainable regional development.

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Analysis of technical evaluation and customer satisfaction of clean water services (case study: PDAM Lematang Enim at Muara Enim Regency, South Sumatra, Indonesia)

Keywords: clean water service, satisfaction, PDAM, water company

Introduction

Water is a basic human need for a variety of residential functions such as drinking, cooking, sanitation, and irrigation. Water has an essential role in human life which is very complex, one of which is to fulfill basic household needs and other activities such as cattle, gardening, crops, food processing, aquaculture, and fisheries (Carrard, Foster & Willetts, 2019). As the years increase, the household's need for clean water will increase due to the number of members in the household. This condition makes water one of the most essential basic needs and cannot be replaced with other resources (Wahyudi, Wahyudi, & Subagya, 2020). Water supply is the distribution of water by governmental utilities, commercial organizations, community efforts, or individuals, typically through a network of pumps and pipes. Public water supply systems are critical to the smooth operation of society. These systems

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provide clean water to people all around the world. Service quality considerations may include supply continuity, water purity, and water pressure. In Indonesia, the regional drinking water company (*Perusahaan Daerah Air Minum* – PDAM), acted as a regional owned enterprise (*Badan Usaha Milik Daerah* – BUMD) – currently manages the need for clean water and drinking water in many areas in Indonesia.

The role of PDAM as a business entity providing clean, healthy drinking water that meets health requirements in an area also focuses on the quality of customer service. Consumer satisfaction with water and service quality does not necessarily correspond to monitored compliance with water and service quality. Consumer satisfaction is defined as contentment or discontent with a service or product based on previous expectations (Qazi, Tamjidyamcholo, Raj, Hardaker & Standing, 2017). Satisfaction can also refer to a person's sentiments of joy or disappointment as a result of comparing a product's performance or results to their expectations (Kotler et al., 2012).

A study by Hakim (2021) indicated that good product quality will affect customer satisfaction, whereas customer satisfaction will affect customer loyalty to PDAM. However, until now, customers are still not satisfied with PDAM services in terms of water quantity, water quality, and water continuity, as well as the increase in water rates (Denantes & Donoso, 2021). The study of Athar, Sutanto and Kusmayadi (2020) presented that drinking water customers are dissatisfied with the quality of service and price, high rate of water loss, clean water distribution and low ability to pay. This problem is expected to reduce the level of customer satisfaction, if the PDAM does not take it seriously (Affandi, Muhammad & Azmeri, 2017).

To fulfill customer satisfaction, PDAM must identify the factors related to customer satisfaction to maximize customer service and company's profits. Customer satisfaction is a buyer's evaluation where the chosen alternative at least provides results (outcomes) equal to or exceeding customer expectations, while dissatisfaction arises if the results obtained do not meet customer expectations (Gunawan, 2022). Service quality factors that have a very high relationship with customer satisfaction are the factors of being responsive and showing sincerity (Syahsudarmi, Tinggi & Riau, 2022), especially in water quality because customers are very concerned about health (Denantes & Donoso, 2021). In additional, the level of customer satisfaction of the PDAM is influenced by water quality, water continuity, water pressure, water meter conditions, repair and maintenance, billing and payment systems as well as water rates and water quality (Dewi & Mursyidah, 2022).

Based on the performance of drinking water company in 2021, the Ministry of Public Works noted that there are 239 PDAMs in the healthy category. Meanwhile, 96 PDAMs are in the unhealthy category and 52 PDAMs are in the sick category. The performance is assessed based on four aspects, namely finance, service, operations, and human resources. Based on the performance evaluation report, it is stated that the service aspect of PDAM Lematang Enim Muara Enim Regency was inadequate and fell into the sick category. In 2021, PDAM Lematang Enim's ranking is in position 99 out of 108, calculated from the performance value of BUMD drinking water per first distribution region with a performance value of 1.81 and a total number of 35,677 customers (Rachman, 2018). This requires changes in service performance at PDAM Lematang Enim to make the PDAM healthier.

Denates and Donoso (2021) investigated the elements that affected consumer satisfaction such as water service quality offered by water supply and sanitation providers in Chile. This research presented that the organoleptics explained by taste, odor, and clarity indicators, are primarily responsible for customer risk perception. The basic drinking water service criteria are intimately related to consumer satisfaction, particularly in terms of quality, quantity, continuity, and affordability (Budiyono, Pamungkas & Darundiati, 2020). The consumer's opinion of water quality and the payment system have the greatest influence on service quality and price. Furthermore, customer satisfaction with water and service quality are negatively impacted by perceived health risk and service quality. Lyimo and Gindo (2022) studied the water supply and sanitation services in Arusha Urban Water Supply and Sanitation Authority in Tanzania. This study found that the cost of water supply and sanitation services has a substantial association with customer satisfaction. Furthermore, research revealed a substantial association between customer happiness and the accessibility of water supply and sanitation services. Customer satisfaction research is critical for pushing service providers to improve their performance.

There have been a lot of research focusing on customers' satisfaction of water company services worldwide, however, there are very limited research investigating at the local perspectives of water company especially in Indonesia. Therefore, this research aims to identify the indicators as well as analyze performance of customer satisfaction at local water company in Muara Enim Regency at South Sumatra Province in Indonesia. At last, this research is expected to give a recommendation to the local government on how to improve the water company's performance.

Material and methods

This research was conducted at Muara Enim Regency, South Sumatra province, Indonesia in which PDAM Lematang Enim is used as a case study. The selection of research locations was carried out purposively with the consideration of the availability of the required data. Muara Enim is a district in South Sumatra, Indonesia which

Ningsih, W., Fitriani, H., Hadinata, F. (2023). Analysis of technical evaluation and customer satisfaction of clean water services (case study: PDAM Lematang Enim at Muara Enim Regency, South Sumatra, Indonesia). *Sci. Rev. Eng. Env. Sci.*, *32* (3), 255–269. DOI 10.22630/srees.4856

has several large rivers as water sources. The research was conducted from January 2022 to September 2022. Interviews were conducted directly with respondents through the help of a questionnaire containing a list of questions related to the performance, service, water distribution, and customer satisfaction of PDAM Lematang Enim. The questionnaires were given to respondents in terms of the performance, service, water distribution, and customer satisfaction of PDAM Lematang Enim.

This research used a cross-sectional design in which the variables including risk factors and effects were observed at the same time as the method of data collection. The data analysis used consisted of an analysis of the customer satisfaction index (*CSI*) and binary logistic regression analysis. An analysis of the *CSI* was conducted to evaluate the satisfaction level of PDAM Lematang Enim Muara Enim service users. The customer satisfaction index is used to determine the overall satisfaction level of PDAM Lematang Enim Muara Enim service users by looking at the level of performance and the level of importance/expectation of service attributes. The magnitude of the value of *CSI* can be explained as follows (Aritonang, 2005):

1. Determine the mean importance score (*MIS*) or the average importance score. This value is obtained from the average level of interest/expectation of service users:

$$MIS = \frac{\left(\text{‰}_{i=1}^{n} Y_i\right)}{n},$$

where n is the number of respondents, and Y_i means importance value of the i-indicator.

2. Calculate the weighted factor (*WF*). This weight is the percentage of the mean importance score value per indicator to the total mean importance score of all indicators:

$$WF = \frac{MIS_i}{\sum_{t=1}^{p} MIS_i} 100\%,$$

where p is p-th importance indicator.

3. Calculating weight score index (*WSI*) or weighted score. This weight is the multiplication between weighted factor and the average level of performance:

$$WSI = WF_i \cdot MPS,$$

where *MPS* is mean performance score.

4. Determine customer satisfaction index (*CSI*):

$$CSI = \frac{\sum_{t=1}^{p} WS_i}{HS} 100\%,$$

where *p* is indicator of *p*-th importance, and *HS* means the highest scale (the maximum scale used).

If the *CSI* value is beyond 50% indicating that the service user is satisfied. In the meantime, if the *CSI* is below 50% it means that the service user is not satisfied. The *CSI* value was divided into five criteria from dissatisfied to very satisfied as seen in Table 1.

TABLE 1. Customer satisfaction index (*CSI*) value criteria

CSI value	*CSI* criteria
$X > 0.80$	very satisfied
0.66–0.81	satisfied
0.51–0.65	quite satisfied
0.35–0.50	less satisfied
0.00–0.34	not satisfied

Source: Pardiyono and Puspita (2020).

Results and discussion

Technical water analysis

The assessment of services provided by the Lematang Enim Regional Drinking Water Company (PDAM), a regional company that provides clean water services is carried out based on the time of water distribution and the quality of the distributed clean water. Distribution time is quite important because it determines the flexibility of service users in utilizing clean water. The quality of water distribution is also an important factor for PDAM Lematang Enim service users because the quality of water will directly be felt by service users.

As seen in Table 2, the schedule for clean water distribution services was divided into five schedule time to ensure the distributed water discharge run effectively.

TABLE 2. Schedule of clean water distribution of PDAM Lematang Enim

Distribution region	Schedule of water distribution
I	08.00–09.30
II	10.00–17.30
III	18.00–21.30
IV	22.00–02.00
V	02.00–05.30

Source: PDAM Lematang Enim.

Since PDAM Lematang Enim as a local water company in Muara Enim regency in South

Sumatra Province in Indonesia has used the river as the main raw water source, it is important to check the water quality based on physical, chemical and microbiologic tests. Several research highlighted that the ingredients of river water sources usually could meet quality standards in physical, chemical and microbiologic indicator tests (Purwono, Ristiawan, Ulya, Matin & Ramadhan, 2019; Widodo, Budiastuti & Komariah, 2019; Novita, Pradana, Purnomo & Puspitasari, 2020). Water quality assessment is carried out through several stages, starting from conducting water sampling and water quality testing. A sampling of customer clean water is carried out at several sample locations to ensure that the water samples can represent the water quality accepted by customers. Table 3 showed that water quality is in a good standard as indicated by the degree of acidity or alkalinity (pH).

TABLE 3. Customer clean water sampling

Sample location	Turbidity [*NTU*]	pH	Residual chlorine content [ppm]
1	3.31	7.02	0.5
2	4.15	7.15	0.6
3	2.91	6.79	0.6
4	3.53	7.01	0.6

Source: Muara Enim Regency Environmental Laboratory.

Physical and chemical tests were then carried out in more detail on the production of water in PDAM Lematang Enim specifically at the water treatment plant (WTP) Talang Jawa as one of the main water processing plant. The test was carried out using six physical indicators and five chemical indicators. The results of the physical test showed that the odor, turbidity, taste, color, TDS, and temperature of the production water in PDAM Lematang Enim WTP Talang Jawa met the applicable requirements. This indicates that there are no organoleptic problems found when observing the clean water. Chemical water examination was carried out by measuring the levels of chloride, nitrite anion, nitrate oxoanion, fluoride, and water pH for pH, phosphate, iron, manganese, copper, zinc, and chromium-T.

After conducting the physical and chemical tests of water based on water quality standards as mentioned in government regulations listed in Table 4, it can be concluded that all of the test results are still within quality standards. This is to show that the raw water from the treatment plant meets the standards for processing until it can be distributed to customers. Furthermore, the chemical tests also showed that the water does not contain excessive certain substances that can cause health problems for consumers. Subsequent checks were carried out to determine the quality of the water directly received by the community using the service. This inspection is important to ensure the quality of water directly received by service users.

The test was carried out through in-depth microbiological water analysis. The microbiology test showed that the water received by consumers meets clean water

TABLE 4. Results of water treatment plant (WTP) tests

Parameter	Unit	Value	Quality standard	Information
Total suspended solids (*TSS*)	$Mg \cdot l^{-1}$	73.00	50	SNI 6989.03.2019
Total dissolved solids (*TDS*)	$Mg \cdot l^{-1}$	78.00	1 000	SNI 6989.27.2019
pH (Lab)	–	7.00	6–9	SNI 6989.11.2019
Phosphate content	$Mg \cdot l^{-1}$	0.4250	0.2	IK 15.20/IK/LME/2022
Iron (Fe) content	$Mg \cdot l^{-1}$	< 0.0366	0.3	SNI.6989.84.2019
Manganese (Mn) content	$Mg \cdot l^{-1}$	< 0.0126	0.1	SNI.6989.84.2019
Copper (Cu) content	$Mg \cdot l^{-1}$	0.0147	0.02	SNI.6989.84.2019
Zinc (Zn) content	$Mg \cdot l^{-1}$	< 0.0068	0.05	SNI.6989.84.2019
Chromium-T content	$Mg \cdot l^{-1}$	0.0064	0.05	SNI.6989.84.2019

Source: Muara Enim Regency Environmental Laboratory.

quality standards as indicated with the results of coliform LB, MPN, and coliform BGLB (Table 5). The results showed that there was no significant contamination of the water quality that was received directly by the community. Drinking water suitable for consumption is drinking water that is clean from contamination and not contaminated by any substances (Wang, Zhang, Lv, Zhang & Ye, 2018). In addition, DAM-treated water must be free of total coliform and *Escherichia coli* content so that it can be suitable for consumption (Latupeirissa & Latupeirissa, 2022).

TABLE 5. Results of water microbiology test (sample taken at 09.45 on 14 October 2022)

<table>
<tr><th rowspan="2">Sample</th><th colspan="3">LB 37°C coliform predictive test [ml]</th><th colspan="3">BGLB coliform affirmation test 37°C [ml]</th><th rowspan="2">MPN count per 100 ml sample</th><th colspan="3">BGLB 44°C coliform assertion test [ml]</th><th rowspan="2">Fecal coliform count per 100 ml sample</th><th rowspan="2">Indicator</th></tr>
<tr><th>10</th><th>1</th><th>0.1</th><th>10</th><th>1</th><th>0.1</th><th>10</th><th>1</th><th>0.1</th></tr>
<tr><td>WIB 84/Labkes (production water)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>≤ 2 (ms)</td><td>0</td><td>0</td><td>0</td><td>≤ 2 (ms)</td><td>5.1.1</td></tr>
</table>

Source: Muara Enim Regency Environmental Laboratory.

Besides the laboratory analysis, the field observations were also conducted to enhance the water quality analysis. It can be seen that the quality of water is appropriate for consumption for the consumers as indicated by being odorless when smelled from far or near, tasteless, and colorless (Latupeirissa & Latupeirissa, 2022). The low concentrations of fecal coliform and total coliform (Table 5) also indicate that the local community living around the river has a high awareness not to dispose of human and livestock waste into the river.

Ningsih, W., Fitriani, H., Hadinata, F. (2023). Analysis of technical evaluation and customer satisfaction of clean water services (case study: PDAM Lematang Enim at Muara Enim Regency, South Sumatra, Indonesia). *Sci. Rev. Eng. Env. Sci.*, *32* (3), 255–269. DOI 10.22630/srees.4856

Customer satisfaction

Satisfaction is a feeling of pleasure or disappointment from someone who comes from a comparison between the impression of the performance of a product (perceived performance) and expectations (Budhi & Sumiari, 2017). Service quality is one of the most important factors in providing satisfaction for the community, especially for businesses engaged in the public sector (Frinaldi & Eka Putri, 2021).

The service quality has a significant influence on customer satisfaction (Dewi & Mursyidah, 2022). The measure of the success of service delivery is determined by the level of customer satisfaction with the product or service because customer satisfaction is achieved if the customer gets the service according to what is needed and customer expectations (Siregar, Syahril & Hanisah, 2020). Consumer interests relate to consumer feelings, such as liking or preference for a product (Liang & Turban, 2011). This interest is driven by motivation to own a product. If the motivation for the object is high, the perception of interest will also be higher (Kotler & Armstrong, 2010). Research shows that company image and service quality have a significant effect on customer interest in owning these products (Rusmiyati & Hartono, 2022).

Based on the questionnaires, the majority of respondents use PDAM services to meet household needs which is around 97%, while other 3% of respondents use PDAM services to meet business or industry needs. These results indicate that PDAM Lematang Enim's services have not been widely used for industrial or business needs. The level of customer satisfaction in this research is defined as a person's feelings after comparing the performance or results he/she feels compared to his/her expectations. Customer satisfaction used in this research is based on some criteria such as tangible, reliability, responsiveness, assurance, and empathy. Table 6 shows the level of customer interest using mean importance score (*MIS*) and mean satisfaction score (*MSS*). The *CSI* calculation is carried out on the weighting of weighted factor (*WF*) and weighted score (*WS*). Total *WS* will be used as the quantifying factor of the *CSI* calculation. It is known that the bigger the *WS* value, the bigger the *CSI* value. The customer satisfaction index (*CSI*) is a measurement to determine the overall level of customer satisfaction by considering the importance of product or service attributes. The results of the *CSI* analysis show that the *CSI* value of service users can be categorized as satisfied. In general, users of clean water services in this study are satisfied with the services provided by PDAM, even though the value of satisfaction received is not the maximum value of satisfaction that can be achieved.

For colorless criteria, the result of questionnaires showed that there is a fairly high level of importance but a low level of satisfaction. The main reasons for customer dissatisfaction are assumed to be related to sensory properties such as water

TABLE 6. Customer satisfaction index (*CSI*) measured by mean importance score (*MIS*) and mean satisfaction score (*MSS*), weighted factor (*WF*) and weighted score (*WS*)

Variable	*MIS*	*MSS*	*WF*	*WS*
Continuous water supply	4.07	3.17	8.89	28.19
Timely supply (when promised)	4.03	3.18	8.79	27.95
Supply consistency	4.04	3.17	8.81	27.93
Accuracy in meter reading/billing	4.10	3.39	8.96	30.32
There is a security guarantee	3.99	3.36	8.71	29.24
Employee competence guarantees a minimum error rate in customer service	4.03	3.36	8.79	29.51
Burst pipe quick repair and service provider bearing the cost	4.03	3.26	8.79	28.66
Pipe repair does not damage other networks	4.19	3.33	9.15	30.50
No smell	4.48	3.40	9.78	33.25
Tasteless	4.42	3.47	9.65	33.46
Colorless	4.43	3.28	9.67	31.72
	CSI			66.14
Category	Satisfied			

Source: own work.

turbidity, rust color, or unpleasant taste and smell (Wang et al., 2018). Based on the study of Latupeirissa and Latupeirissa (2022), customer satisfaction is mostly influenced by the water clarity, water smell, water taste, chemical content, water availability, operator alertness in installing new connections, water meter readings, repairing damage to water meters, and swiftness or speed in handling piping complaints. Therefore, the water consumption has the characteristics of being odorless when smelled from far or near, tasteless, and colorless (Latupeirissa & Latupeirissa, 2022).

For tastelessness and odorlessness variables as two important indicators that must be maintained, the results showed that there is a high importance and satisfaction values compared to other indicators. However, these two indicators also still require improvement in terms of performance to maximize customer satisfaction. There is an urgency to maintain and even improve performance on these two indicators, because these two indicators are included in the second quadrant (Fig. 1), which has the potential to become a superior service for PDAM Lematang Enim. In this case, customers should not have unpleasant experiences from drinking water, especially in terms of taste and odor (Denantes & Donoso, 2021).

Other indicators such as the accuracy in meter reading or billing, security guarantees, employee competence or knowledge, customer service, and pipe repair are not that much important and have low level of satisfaction based on customers'

Ningsih, W., Fitriani, H., Hadinata, F. (2023). Analysis of technical evaluation and customer satisfaction of clean water services (case study: PDAM Lematang Enim at Muara Enim Regency, South Sumatra, Indonesia). *Sci. Rev. Eng. Env. Sci.*, *32* (3), 255–269. DOI 10.22630/srees.4856

perspectives. These indicators fall into the category of third quadrant – low priority (Fig. 1). Performance improvement in this quadrant needs to be considered, because this attribute is considered as less important influence for customers, and the performance also is not very important (Setyaningrum, 2020). The successful measure of service delivery is determined by the level of customer satisfaction. Customer satisfaction will be realized if the services provided are in accordance with the established service standards or better than the established standards, while dissatisfaction arises when the results obtained do not meet customer expectations (Suandi, 2019; Aulia & Syarvina, 2022).

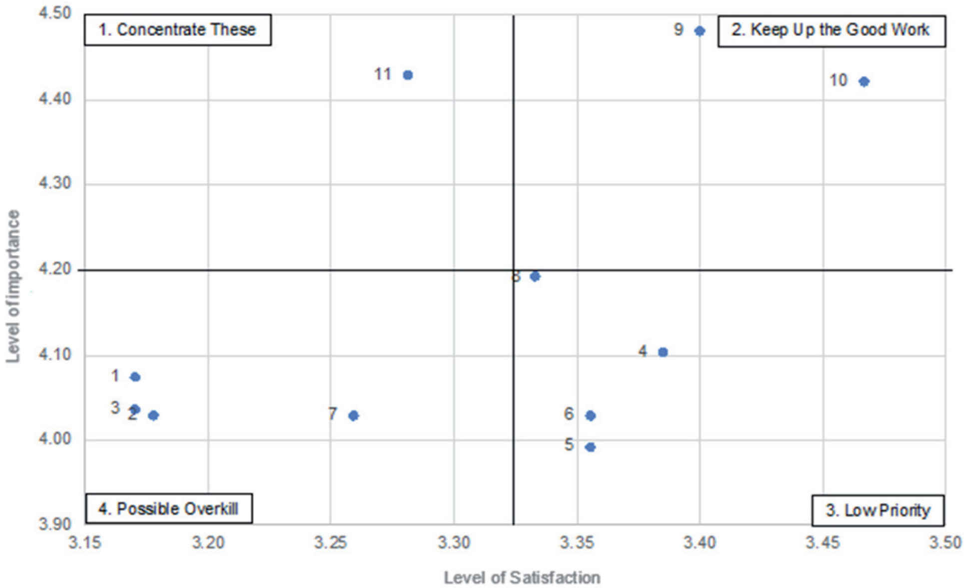

FIGURE 1. Quadrant classification based on level of satisfaction and level of importance
Source: own work.

Improvement of water distribution quality performance is therefore required to improve the service performance of PDAM Lematang Enim. As performance increases, it will increase customer satisfaction, because service quality has a close relationship with customer satisfaction (Tijjang, Nurfadhilah & Putra, 2020). It can be concluded that there is a positive relationship between service quality and customer satisfaction (Nyabundi, Aliata & Odondo, 2021) especially in the aspect of assurance. It is also essential to reduce the service gaps to provide superior service quality to retain existing customers as well as to attract new customers (Nyabundi et al., 2021).

Improvement strategy for customer satisfaction

The way to improve customer satisfaction with the services provided by PDAM Lematang Enim must be carried out to ensure the loyalty of costumers as the service quality has a positive effect on customer loyalty (Hakim, 2021). Therefore, the effective strategies are required to improve the actual conditions of water services. The analysis carried out to support the formulation of the strategy is through a strength, weakness, opportunity, and thread (SWOT) analysis. The strategies developed to improve customer satisfaction formulated based on the SWOT analysis has been conducted to create effective and efficient strategies. In addition, the results of the quadrant analysis are also used to ensure that the strategies are in line with the scale of importance and contribution of PDAM performance perceived by customers.

As seen in Table 7, there are three variables that become the strength to improve customer satisfaction such as the extensive water distribution network, good staff service and good experience of staffs and technicians. This strength can be developed to reduce potential losses due to perceived weaknesses as shown by the variables such as low water discharge, low quality of clean water, low streaming frequency, and short duration of water flow. Nonetheless, potential optimization and threat minimization also need to be carried out to ensure that the existing strategy can run according to the predetermined plan.

TABLE 7. SWOT analysis

Strength	Weaknesses
1. Extensive water distribution network 2. PDAM staff service is good 3. PDAM staff and technicians have good experience	1. Low water discharge 2. Low quality of clean water from the source 3. Low streaming frequency 4. Short duration of water flow per consumer (continuity)
Opportunity	**Threats**
1. The potential of water resources in Muara Enim 2. Community loyalty to PDAM Lematang Enim services	1. The increase in population and disposal sites that threatens the quality of clean water

Source: own work.

The formulation to improve customer satisfaction and loyalty can be done by doing the first job right. In addition, complaint handling is proven to influence customer loyalty (Hermawati, 2022). The water supply companies must improve performance if customer expectations are greater than actual conditions (Anggraini, Shalihati, Bachtiar & Suhendi, 2020). Improving service quality can also be done by mapping the factors that affect customer satisfaction with service quality (Ridha, Marissa & Marpaung, 2020).

Several strategies taken by PDAM Lematang Enim to improve service satisfaction may include focusing on improving relevant variables such as water quality (colored and odorous water), water discharge, water distribution continuity, and efficient and targeted pipe repairs without damaging the existing network. The distribution of resources towards office staff services, and waiting rooms are considered less important to consumers so that they can be diverted towards improving water quality and water continuity. Other strategies to increase customer satisfaction could be done by improving the quality of water supply, replacing water meters regularly, improving the compensation claim system, identifying complaints that have the potential to reduce the PDAM's reputation, and maximizing the use of social media for information tools to customers (Anggraini et al., 2020).

It is also important to use technology and educate the community on the effective and efficient use of clean water, as well as the development of standardized disposal sites. The use of technology in the PDAM system needs to be done to support the improvement of clean water quality and continuity, while education of the community is important to ensure the support from the community to improve the quality of clean water in the regency. The marketing communications can also be done by utilizing digital technology to provide quick information to customers. Social media platforms are one example of digital technology that companies usually use to handle customer complaints, as they can provide quick and detailed responses to customer complaints (Golmohammadi, Havakhor, Gauri & Comprix, 2021). In addition, PDAM Lematang Enim can also educate through the selection of "water ambassadors", as done by PDAM Tirta Pakuan, which is proven to be more attractive and memorable to customers (Anggraini et al., 2020).

Conclusions

PDAM Lematang Enim has generally carried out operational activities quite well. The *CSI* score showed that a value of 66.14 can be grouped in the Satisfied category. The level of customer satisfaction with the services provided by PDAM Lematang Enim can be categorized as good. The performance of PDAM Lematang Enim, in terms of physical evidence, reliability, responsiveness, assurance, empathy, distribution quality, and customer satisfaction according to customers is quite good. Factors that influence customer satisfaction are clean water discharge, clean water quality, and pipe leak repair services by PDAM Lematang Enim. Strategies that can be done to increase customer satisfaction include focusing improvements on variables that are important to the community, using appropriate technology, and educating the community about clean water management systems.

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Summary

Analysis of technical evaluation and customer satisfaction of clean water services (case study: PDAM Lematang Enim at Muara Enim Regency, South Sumatra, Indonesia). The availability of clean water is the responsibility of the local government to the community by one of the regional-owned companies known as the regional drinking water company (*Perusahaan Daerah Air Minum* – PDAM). The company performance will greatly affect community satisfaction. This study aims to analyze the performance of PDAM Lematang Enim and assess customer satisfaction with them. The data used in this study were collected through laboratory analysis and direct surveys of the community. The data were then analyzed using quantitative statistical methods. Customer satisfaction index (*CSI*) analysis and quadrant analysis are used to map customer satisfaction with the services provided. The *CSI* score showed that a value of 66.14 can be grouped in the satisfied category. The level of customer satisfaction with the services provided by PDAM Lematang Enim can be categorized as good. Strategies for increasing customer satisfaction are formulated through strength, weaknesses, opportunities, and threats (SWOT) analysis. The results of the analysis show that customer satisfaction is included in the satisfied category. Water quality variables include that water does not smell and tastes quite good, but customers still feel that the water they receive has a different color. Strategies that can be implemented to increase customer satisfaction include focusing on increasing the most important variables according to customers, reducing spending on less important variables, and optimizing the use of appropriate technology.

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Designing optimal solar water pumping stations for irrigation of agricultural lands

Keywords: solar panel, optimization system, buck converter, FLC, engineering model, fill factor

Introduction

The irrigated lands allocated for agricultural purposes on the planet, according to the forecasts of the UN experts, in 2050 will have an acute shortage of water resources. In accordance with the forecasts of these experts, water resources will become very valuable and scarce in the near future. One of the main causes of uncultivated agricultural lands is the poor condition of the irrigation water system and in some cases its absence.

In a number of developing countries, the irrigation of agricultural lands, especially the lands near the houses, is often carried out with potable water, as a result of which large losses of potable water occur, which in turn leads to the shortage of potable water.

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In order to minimize the drinking water losses, the irrigation of lands should be carried out with water resources from rivers, natural lakes, reservoirs and other water sources, which is both economically efficient and useful from the point of view of irrigation.

It should be noted that in agricultural lands, as a rule, medium and small rivers flow near owned irrigation lands, but the irrigation of these agricultural lands mostly continues to remain unirrigated. One of the main reasons for the impossibility of organizing irrigation is the lack of access of the agricultural enterprises to the power grid.

If new technologies and financial investments in the water transportation and management system are not implemented in the irrigation system of lands, then the water deficiency will deepen in these countries.

Thus, irrigation water systems must be modernized, old ones restored, existing ones used sparingly and managed efficiently.

There are many scientific and practical justifications that prove that it is effective to use solar water pumping stations for irrigation of agricultural lands, in which it is necessary to use new irrigation management technologies, such as drip irrigation and the development and implementation of an automated remote control system. This will contribute to solving a number of environmental problems, such as reducing CO_2 emissions and increasing irrigated agricultural lands, which in turn will lead to improved yields.

According to the European Energy Commission (EEC):

– the level of environmental pollution is proportional to the level of energy consumption;
– given the observed rate of growth in energy consumption, a global energy catastrophe is possible by 2050.

One of the ways to solve this problem is using renewable power sources: solar, wind, bioenergy, etc. It has been established that the energy received by the Earth from the Sun per hour is equal to the total amount of power consumed by people in a year. More attention is paid to the development of energy based on the use of solar radiation, which is associated with a number of factors: environmental safety and the unlimited supply of solar energy. Photovoltaics is one of the main directions in the field of solar energy. The photovoltaic effect is the direct conversion of solar energy into electrical energy. Recently, solar panels have found much needed applications in irrigation systems. Solar panel pumps, which pump water from rivers and from deep aquifers.

To optimize the conventional solar water pumping station, its optimal point (at a given condition) is tracked, using online or offline algorithms, and the system operating point is forced toward this optimal point. There are various kinds of optimization methods reported (Deokar, Bindu & Deokar, 2021; Gevorkov,

Haase, G., Kirakossian, G. T., Kirakosyan, G. H., Mkrtchyan V. A. (2023). Designing optimal solar water pumping stations for irrigation of agricultural lands. *Sci. Rev. Eng. Env. Sci.*, *32* (3), 270–283. DOI 10.22630/srees.4994

Domínguez-García & Romero, 2023) and one of the optimization methods which have demonstrated a solar pumping system's fine performances and high accuracy under different environmental operating conditions is the fuzzy-based optimization method. Solar water pumping stations are recognized as a sustainable and environmentally friendly solution to provide water for irrigation of lands.

The goal of this article is the calculation, computer simulation, and optimization of the important engineering parameters, which are the water discharge rates of the local networks of solar water pumping stations driven by the DC motors.

Engineering model of the solar water pumping stations

The station mainly comprises a solar panel, a centrifugal pump load driven by a DC motor, and a reservoir as shown in Figure 1.

The engineering model of a solar water pumping station differs from q_e the model of a solar water pumping system in that the station includes a water reservoir with a network of water lines. Water from the river is pumped into the reservoir by a pump and each land user can turn on the water on his land plot for irrigation. The main purpose of the reservoir is to automatically maintain a predetermined water level. The change in the level (Δh) depends on the difference in flows ($Q - q$), where Q is

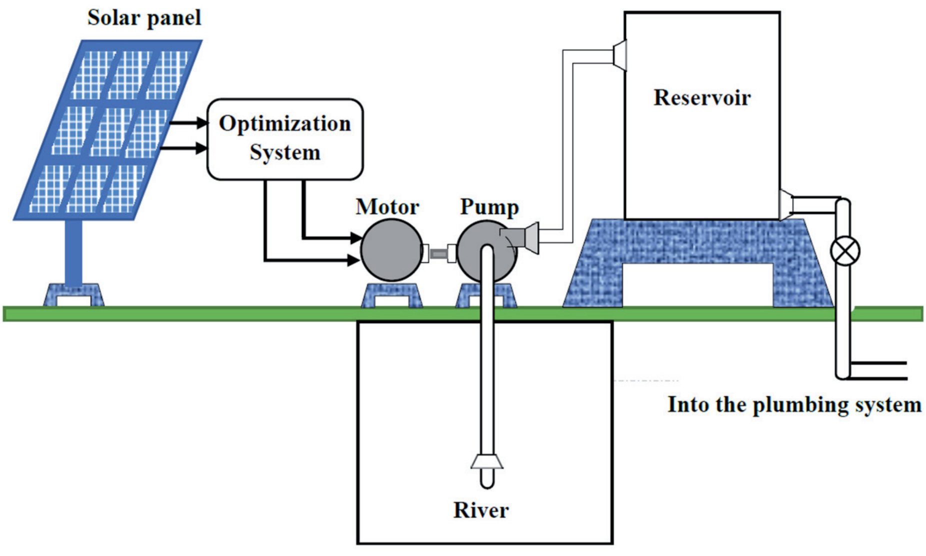

FIGURE 1. The scheme of the solar pumping station

Source: own work.

the incoming water flow, q is the outgoing water flow and S is the cross-sectional area of the reservoir. We will assume that one of the land users always has water turned on and the pump is constantly working to pump water into the reservoir during the daytime. The reservoir can operate in series or parallel modes of irrigation of land located near the river and extending along the river. The parallel irrigation mode is achieved due to the increased activity of the pump, which twitches all the time. In this case, the mechanical parts of the pump wear out, and its service life is significantly reduced. It is found that the solar panel energy utilized by the centrifugal pump is much higher than the energy consumed by the volumetric pump. In fact, in the case of centrifugal pumps, the operation takes place for longer periods even for low solar radiation levels, and the load characteristic is in closer proximity to the solar panel optimal point.

The topology of the global network of solar pumping stations is illustrated in Figure 2.

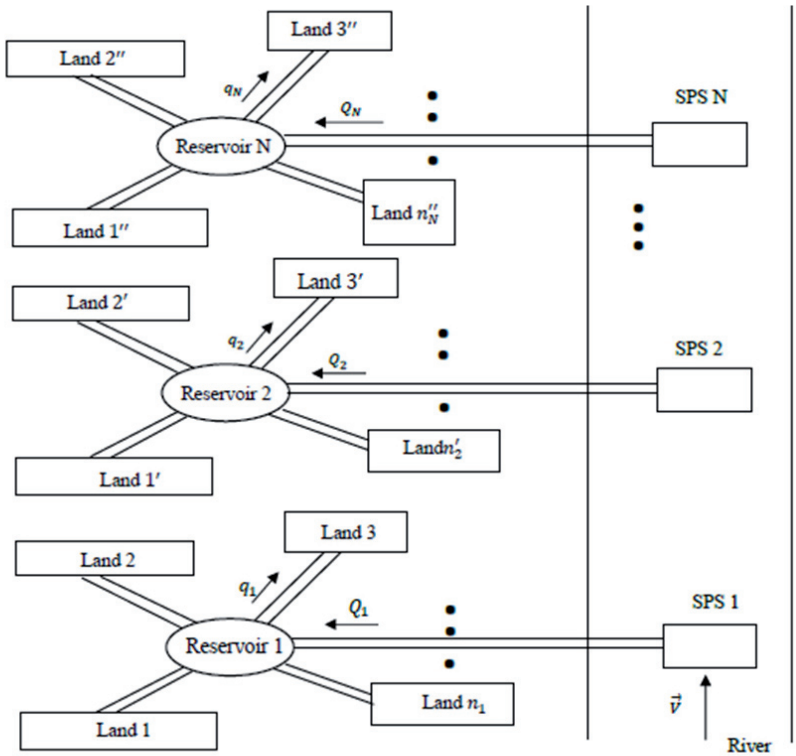

FIGURE 2. The topology of the network of solar pumping stations

Source: own work.

The reservoir is connected to the lands using a network of water pipes. The local network of the solar pumping station is a solar pumping system including a network of water pipes. The local networks of solar pumping stations are installed along the river equidistant in a consistent manner.

The right side of Figure shows 2 solar pumping systems (SPS), and the left one the reservoirs with inflow (Q_i) and outflow (q_i) pipes of a water network. During a small interval Δt, the volume of water added to the i-th reservoir by the pump is $Q_i\Delta t$, and the volume of water flowing out of the i-th reservoir is equal to $q_i\Delta t$. Given that the cross-sectional area of the reservoir is equal to S_i, we obtain a change in the water level in the i-th reservoir

$$\Delta h_i = \frac{Q_i - q_i}{S_i}\Delta t. \tag{1}$$

Since the topology of the global network of solar pumping stations is a superposition of the topologies of the local networks of solar pumping stations, the amount of pumped water per day is an additive quantity. The water discharge rate (Q) for the global network of solar pumping stations is given by

$$Q = \sum_{i=1}^{N} Q_i, \tag{2}$$

where Q_i is the incoming water flow to the i-th reservoir of solar water pumping stations. This means that in order to optimize a solar pumping station, it is necessary and sufficient to maximize the water discharge rate for one local solar pumping system. Therefore, in the future, we will consider the model of one local network of the solar pumping system.

The simulation model of the solar pumping system

Figure 3 shows the scheme of the solar water pumping system. The solar panel directly converts solar radiation into DC electrical power. The magnitude of the solar panel current depends upon the intensity of solar radiation. The solar panel is connected to the DC/DC buck converter with an optimization technique, which allows matching the load characteristics with the solar panel characteristics.

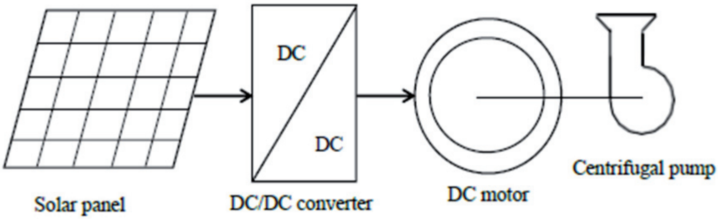

FIGURE 3. The solar pumping system scheme
Source: own work.

The DC/DC buck converter modeling

The DC/DC buck converter is the main part of the optimization system. As the name implies, the average output voltage is less than the DC input voltage. Here, switching control is done by a power insulated gate bipolar transistor. When the transistor is switched on, the diode D_1 becomes reverse-biased and the input provides energy to the load as well as to the inductor. When the transistor is switched off, an inductor current flows through the flywheel diode D_1, transferring some of its stored energy to the load. This inductor current falls until the transistor is switched on again in the next cycle. The filter capacitor at the output is assumed to be very large, so that a nearly constant instantaneous output voltage is obtained.

Thus, by varying the fill factor of the insulated gate bipolar transistor, we can vary the average output voltage and output power. The regulation is generally achieved with a pulse-width modulation technique at a fixed frequency and the fill factor γ can be defined by the following equations:

$$\frac{V_o}{V_s} = \gamma, \tag{3}$$

$$\frac{I_o}{I_s} = \frac{1}{\gamma}. \tag{4}$$

Since we are dealing with non-linear energy sources here, a fuzzy logic controller (FLC) will be used to find the optimal point on the solar panel's current-voltage characteristic. Usually,a DC/DC buck converter is utilized between the solar panel and the pump load for optimization system. A functional block diagram of FLC is shown in Figure 4.

Haase, G., Kirakossian, G. T., Kirakosyan, G. H., Mkrtchyan V. A. (2023). Designing optimal solar water pumping stations for irrigation of agricultural lands. *Sci. Rev. Eng. Env. Sci.*, *32* (3), 270–283. DOI 10.22630/srees.4994

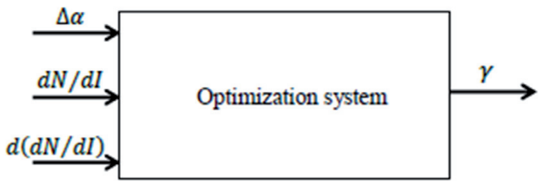

FIGURE 4. The general diagram of the proposed fuzzy logic controller (FLC)
Source: own work.

The FLC is a multiple input multiple output system where the input parameters are dN/dI, $d(dN/dI)$ and $\Delta\alpha$. Fill factor γ is the output parameter of the MIMO system. As a term-set of the input variable dN/dI we will use the set

$$\frac{dN}{dI} = \{negative\ big, negative\ small, zero, positive\ small, positive\ big\}$$

or in symbolic form $\frac{dN}{dI} = \{NB, NS, Z, PS, PB\}$ with triangular membership functions. A similarterm-set is also considered for the input variable $d(dN/dI)$ and the output variable γ. As a term-set of the input variable $\Delta\alpha$ we will use the set $\Delta\alpha = \{negative, zero, positive\}$ or in the symbolic form $\Delta\alpha = \{N, Z, P\}$ with triangular membership functions.

The input and output parameters of the multiple input multiple output system are related by the following relationships:

$$\frac{dN}{dI} = \frac{NA(j) - NA(j-1)}{IA(j) - IA(j-1)}, \tag{5}$$

$$d\left(\frac{dN}{dI}\right) = \frac{dN}{dI}(j) - \frac{dN}{dI}(j-1), \tag{6}$$

$$\Delta\alpha = d\gamma(j-1), \gamma(j) = \gamma(j-1) + d\gamma(j), \tag{7}$$

where $NA(j)$ is the output power of the solar panel and $\gamma(j)$ is the fill factor of the DC/DC buck converter at j-th iteration number. The iteration is stopped when $\gamma(j)$ is approximately equal to $\gamma(j-1)$.

The algorithm for calculating the output parameter γ for FLC (Fig. 4) according to the fuzzy logic is carried out by Eqs (5)–(7), and the steps of this algorithm are described in the work by Kirakosyan, Avetisyan, Kondjoryan and Kirakosyan (2014).

The DC motor model

The simulation model of a DC motor is a single input single output system that has one input $V_{app}(t)$ – voltage, and one output $\omega(t)$ – angular speed of the rotor.

In this model, the dynamics of the motor itself are idealized; for instance, the magnetic field is assumed to be constant. The resistance of the circuit is denoted by R and the self-inductance of the armature by L.

The electromagnetic torque τ acting on the motor shaft is proportional to the induced current $i(t)$ and has the form:

$$\tau(t) = K_m i(t), \tag{8}$$

where K_m is the coupling coefficient between armature current and electromagnetic torque. The induced electromotive force V_{emf} is proportional to the angular velocity of the rotor ω and is expressed by the formula:

$$V_{emf}(t) = K_b \omega(t), \tag{9}$$

where K_b is the coupling coefficient between angular velocity and back electromotive force.

The mechanical part of the motor equations is derived, using Newton's law, which states that the inertial load J times the derivative of the rotor angular speed equals the sum of all the torques about the motor shaft. The resulting equation can be written in the form:

$$J\frac{d\omega}{dt} = \sum \tau_i = -K_f \omega(t) + K_m i(t), \tag{10}$$

where $K_{f\omega}$ is a linear approximation for viscous friction.

Finally, the electrical part of the motor equation is given by

$$V_{app}(t) = L\frac{di}{dt} + Ri(t) + K_b \omega(t). \tag{11}$$

This sequence of equations leads to a set of two differential equations that describe the behavior of the motor, the first for the induced current:

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$$\frac{di}{dt} = \frac{-R}{L}i(t) - \frac{K_b}{L}\omega(t) + \frac{1}{L}V_{app}(t), \tag{12}$$

and the second for resulting rotor angular speed:

$$\frac{d\omega}{dt} = \frac{-1}{J}K_f\omega(t) + \frac{1}{J}K_m i(t). \tag{13}$$

Rewrite the system of equations in a matrix form:

$$\frac{d}{dt}\begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & \frac{-K_m}{L} \\ \frac{K_m}{J} & \frac{-K_f}{J} \end{bmatrix}\begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}V_{app}(t), \tag{14}$$

$$y(t) = \begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix}V_{app}(t). \tag{15}$$

We can construct single input single output models using simple commands in the Control System Toolbox. The state of the system in this case is often written as a column vector $x = [i(t), \omega(t)]^T$. The applied voltage V_{app} is the input of the system $u = V_{app}$, and the angular velocity ω is the output $y = \omega$.

The centrifugal pump model

The mechanical part modeling of an electric motor is given by:

$$J\frac{d\omega}{dt} = k_m i(t) - k_f\omega(t) - \tau_L, \tag{16}$$

where k_f is the viscous-friction coefficient, J is the total inertia of the motor shaft, and τ_L is the load torque.

In this case, τ_L is the hydrodynamic load torque of the centrifugal pump, which is given by the following equation:

$$\tau_L = \tau_N = A_N\omega^2, \tag{17}$$

where:

$$A_N = \frac{N_n}{\omega^3}. \tag{18}$$

The centrifugal pump is also described by an $H(Q)$ characteristic given by:

$$H(Q) = C_1\omega^2 - C_2\omega Q_i - C_3Q_i^2, \tag{19}$$

where C_1 is the constant parameter corresponding to the «shut off» point, C_2 is the constant parameter corresponding to the «peak head» point and C_3 is the constant parameter corresponding to the «best-efficiency» point.

The pump performance is predicted by specifying a load curve:

$$H = H_g + \Delta H, \tag{20}$$

where H_g is the geometrical height which is the difference between the free level of the water to pump and the highest point of the piping circuit, and ΔH is the friction losses in the piping circuit, which depend on the flow rate. The pump functioning point can be obtained by the intersection point of the pump characteristic and load curve (Kenge, Hasija, Tare & Raghuwanshi, 2020).

Results and discussion

For the engineering parameter optimization, the linguistic description is expressed in termsof IF-THEN statements and the following fuzzy logic inferences:

- RULE_1: IF dN/dI is PB and $\Delta(dN/dI)$ is PB and $\Delta\alpha$ is P then γ is NB.
- RULE_2: IF dN/dI is PB and $\Delta(dN/dI)$ is NS and $\Delta\alpha$ is P then γ is PS.

Fuzzy inference systems are designed to transform the values of input variables of the control process into output variables based on the use of fuzzy production rules. To do this, systems must contain a base of rules for fuzzy productions and implement fuzzy conclusions based on premises or conditions presented in the form of fuzzy linguistic statements. Inference fuzzy rules for the local network of solar pumping stations include 85 fuzzy control rules. In this section, the simulation results of the fuzzy water discharge rate optimization of a solar pumping station driven by a DC motor coupled to a centrifugal pump are presented. Based on the proposed fuzzy optimization method, we investigated the water discharge rate for the solar water pumping station (Nawel, Mourad & Mongi, 2019; Ghosal, Badra & Sahoo, 2021; Singh, Yadav, Kumar & Kumar, 2022). The optimization of the water discharge rate is carried out by maximizing the power of the centrifugal pump for a given intensity of solar radiation (E), which varies slowly with time. This will consequently tend to maximize the DC motor speed (Nasir, 2019; Ganesh, Siva & Rao, 2020; Jafarkazemi & Dabaghi, 2021).

The motor dynamic model associated with the mechanical differential Eq. (16) is solved using the fourth-order Runge–Kutta numerical method. Then, the water discharge rate is calculated using Eqs (19) and (20).

We can write a computer program using MATLAB to evaluate the water discharge rate using Eqs (19) and (20). Such a program is the M-file named pump.m and can be called as follows:

```
>> x = 0: 0.1: 20;
>> plot(x, pump(x)); gridon;
>> x1 = fzero('pump',[0   20])
x1 = 1.99.
```

Listing of the M-file pump.m is as follows:

```
function f=pump( x )
%water discharge rate
lambda=0.0396;
l=7.4;
d=0.1;
xi=4.3;
omega=188.336;
g=9.8;
H=7.4;
C1=4.9234*exp(-2);
C2=8.5825*exp(-5);
C3=-0.041;
f=C1*(omega^2)-C2*omega*x-C3*(x.^2)-H(lambda*(l/d)+xi)*((8*(x.^2))/((pi^2)*(d^4)*g));

end
```

The optimization of the solar water pumping station driven by the DC motor was carried out using fuzzy logic, and the simulation results are shown in Table 1.

TABLE 1. Simulation results of the solar water pumping station with fuzzy optimization

E [W·m^{-2}]	Non-optimized ω [rad·s^{-1}]	Optimized ω [rad·s^{-1}]	Q_i [m^3·h^{-1}]
1 000	188.237	188.336	1.99
900	182.228	182.634	1.93
800	173.956	175.725	1.85
700	164.101	168.152	1.77
600	152.706	159.748	1.68
500	136.746	150.269	1.58
400	121.999	139.333	1.47
300	106.254	126.271	1.33
200	85.644	109.724	1.00

Table 1 also summarizes the simulation results of the non-optimized and optimized solar water pumping system driven by the DC motor, for some solar radiation intensity levels. This explicitly shows the significance of the proposed fuzzy optimization algorithm in terms of the increase in water discharge rates.

Conclusions

This article presents the mathematical modeling of the global network of solar pumping stations for irrigation using MATLAB environment. We have demonstrated that the best method to perform the functioning of the local networks of Solar pumping stations is to introduce the optimization system for the DC/DC buck converter, in particular for the local networks of stations functioning without batteries.

The advantages of the global network of solar pumping stations with the fuzzy--based optimal point tracker over the conventional global network of solar pumping stations include:

1. The online adaptive search of the local network optimal points;
2. Robustness to environmental conditions and parameter variations;
3. High accuracy under different operating conditions;
4. No need for external sensors to detect solar intensity and temperature.

It is clear from the results that DC motor speed, power, and water discharge rate increase when solar insolation increases.

In MATLAB, we have developed a simulating program based on the obtained adequate mathematical models of different components of the solar water pumping station.

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Summary

Designing optimal solar water pumping stations for irrigation of agricultural lands. An investigation into the design of a stand-alone solar water pumping station for supplying rural areas is presented. It includes a study of system components and their modeling. The solar water pumping station comprises a solar panel, DC/DC buck converter, DC motor driving a centrifugal pump, and a reservoir. The fuzzy-based maximum power point tracker is developed to optimize the drive speed and the water discharge rate of the coupled centrifugal pump. These use dN/dI, $d(dN/dI)$ use parameters, and a variation of the fill factor $\Delta\alpha$ input variables. The proposed solution is based on a judicious fuzzy adjustment of a converter fill factor, which adapts the load impedance to the solar panel online. The simulation results show the effectiveness of the drive system for both transient and steady-state operations. Hence, it is suitable to use this fuzzy logic procedure as a standard optimization algorithm for such solar water pumping stations. The modeling is carried out in MATLAB/Simulink.

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Performance of self-compacting concrete cast in hot weather conditions

Keywords: self-compacting concrete, rheological properties, compressive strength, splitting tension, silica fume, fly ash, hot weather, casting, retarder

Introduction

A special kind of concrete known as self-compacting concrete (SCC) can compact itself with no need for external vibration. It is distinguished by its capacity to flow, cover deeply recessed narrow members and create uniformly integrated concrete members free of bleeding or segregation traces. This performance cannot be accomplished by using regular concrete in the usual manner. Studies were conducted to ascertain and assess the properties of SCC. These studies served as the foundation for the development of SCC standards (ETS Committee, 2009).

Professor Hajime Okumura first suggested the idea of SCC in 1986, but the prototype was first created by Professor Ozawa at the University of Tokyo in Japan in 1988 (Ozawa, Mackawa & Kunishima, 1989; Okamura & Ozawa, 1995). The same elements that make up traditionally vibrated concrete – cement, aggregates, and water – as well as different quantities of chemical and mineral admixtures – make up SCC's ingredients. High-range water reducers (super-

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plasticizers) and viscosity-enhancing compounds are the most frequently used chemical admixtures because they alter the rheological characteristics of concrete. Mineral admixtures are used in the manufacturing of SCC because they not only offer financial advantages, but also lower water heat. Additionally, some mineral admixtures are known to enhance the workability and long-term performance of concrete (EFNARC, 2002; Ahmed, Seleem, Badawy & Elakhras, 2016), as well as enhance its rheological characteristics and decrease the thermally induced cracking (Bilodeau & Malhotra, 2000; Dinakar, Babu & Santhanam, 2008). Silica fume (SF), fly ash (FA) and limestone powder (LP) were used the most in SCC (Bouzoubaâ & Lachemi, 2001; Türkmen, 2003; Nehdi, Pardhan & Koshowski, 2004; Felekoğlu, Tosun, Baradan, Altun & Uyulgan, 2006; Esping, 2008; Khatib, 2008; Leemann, Loser & Münch, 2010).

Silica fume, and fly ash and some other materials were also used to produce sustainable concrete. Najaf, Abbasi and Zahrai (2022) investigated the impact of using micro silica, waste glass powder and polypropylene fibers together in order to obtain sustainable lightweight concrete, which has high compressive strength, flexural strength, ductility and impact resistance. The use of micro silica as partially replacing cement and waste glass powder replacing some aggregates had its beneficial environmental impact. It was found that the best percentages of 10% micro silica, 25% glass powder and 1.5 wt.% of fibers improved significantly its compressive strength and flexural strength of light weight concrete and also increased its impact resistance. It was mentioned that using micro silica as partially replacing cement by 10 wt.% could reduce the amount of CO_2 produced by 5 t while constructing a 5-story building and that had its valuable effect on the environment. Lightweight aggregates (Mueller, Metcherine & Haist, 2001) and recycled concrete aggregates (Corinaldesi & Moriconi, 2003; Tu, Jann & Hwang, 2005) were also utilized in SCC. Increased viscosity may be necessary to lower the possibility of segregation because lightweight aggregate has a tendency to float (Shi & Yang, 2005). The water absorption of aggregate made from recycled concrete may greatly affect the filling ability as a result of fast losing of consistency.

The impact of aggregate types (gravel, dolomite and basalt) and the impact of sand to aggregate ratio on SCC characteristics was researched by Seleem, Badawy and Shehabeldin (2006). Survey outcomes showed that the optimum recommended values of sand to aggregate ratio were found to be 47.5% for gravel SCC and 50% for basalt SCC. At sand to aggregate ratio of 47.5%, the best flow behavior was recorded for dolomite SCC while basalt SCC recorded the worst behavior.

Khalil, H. S., Abd Elhameid, M. W., Badawy, A. A. (2023). Performance of self-compacting concrete cast in hot weather conditions. *Sci. Rev. Eng. Env. Sci.*, *32* (3), 284–302. DOI 10.22630/srees.4867

Khalil (2008) studied the impact of delay time on the rheological and strength characteristics of the SCC mix; the amount of time from the conclusion of the mixing process until the beginning of concrete placement, or even its end, and the function of using a retarding admixture with the SCC mix. It was discovered that as the delay time grew, the rheological characteristics of the SCC blend gradually decreased to the point where some of the SCC limits were not met at a delay time of 30 min. Even with a 30 min time delay, the inclusion of 0.5% retarding admixture could bring the mixture's rheological characteristics within the SCC limits (Khalil, 2008).

Saafan and Bait Al-Shab (2020) investigated the behavior of SCC under simulated hot weather conditions as Climate has been an issue to consider during the last years and the ambient temperature is more critical for SCC than conventional concrete and SCC basic requirement is related to its consistency and ability to flow during placement. The studied parameters involved the ambient temperature, materials temperature and using a retarder. Tests performed included the measurement of the rheological properties, compressive strength and early shrinkage. Temperature of the thermally insolated chamber, mixing water and the solid materials ranged between 50°C and the ambient temperature of 25°C in different combinations. The rheological properties were adversely affected by temperature and an enhancement in performance was obtained by cooling of the concrete materials and using a retarder. Using a retarder resulted in an adverse effect on the compressive strength results between 7 and 90 days under simulated hot weather conditions. The effect of time delay of 20 min before casting was also considered.

Aim and research significance

The production of SCC in the laboratory and the investigation of the effect of various parameters on its behavior showed high sensitivity for this type of concrete to temperature; an increase in the ambient temperature of few degrees was sufficient for SCC to lose its required rheological characteristics and did not satisfy its rheological limits, which were necessary for its use. In addition, the work in situ on a large scale is different from working in a controlled environment such as the laboratory. Therefore, the aim of this work is to develop a suitable SCC design mix based on experience to be used in situ under hot weather conditions of about 35°C and to study the characteristics of this mix as well as the impact of various ingredients of the SCC mix on its rheological and hardened properties under such conditions. Intended variables are the cement content, ratio of coarse to fine aggregate, water to cement ratio, chemical admixture content and mineral admixture content such as fly ash or silica fume.

The experimental work

Cement from the Suez Corporation in Egypt, Category I ordinary portland cement (C42.5), was used. Natural siliceous sand as a fine aggregate and pulverized limestone as a coarse aggregate with 14 mm maximum particle size was used. The specific gravity and water absorption for sand and limestone aggregates were 2.63%, 0.65%, and 2.61%, 0.8%, respectively. With a water-cementitious materials ratio of 0.45, clean tap water was used. The chemical admixture used was a high-ranged super plasticizes from Basf company called Master Glenium RMC 315. Besides, SF and FA were used in SCC mixes to determine how well the mineral admixtures performed. Silica fume and fly ash used in this study were from Sika Company in Obour city, Egypt and FA was categorized as Class C in accordance with the ASTM C 618 standard (ASTM International [ASTM], 2023).

According to the Egyptian Technical Standards for SCC (ETS Committee, 2009), the SCC mixtures were prepared. The amounts of ingredients needed for one cubic meter of concrete are listed in Table 1. One mix served as the control, while the other eleven mixes with mineral admixtures were made in various configurations. Table 1 provides the ratios of different combinations. The chemical admixture, viscosity enhancing admixture (VEA), was used with a ratio of 2% of the cement content. Silica fume was added at 2 proportions (5%, 10%) as a substitute for some of the cement content. The fly ash was added by 2 proportions (25%, 35%) as a substitute for some of the cement content.

TABLE 1. Amounts of materials needed for 1 m^3 of self-compacting concrete (SCC) mixes

Mix code	Cement content [kg·m^{-3}]	Mineral admixture			Coarse to fine aggregate ratio (C : $F_{agg.}$)	Dolomite content [kg·m^{-3}]	Sand content [kg·m^{-3}]	Water to cement ratio (w/c)	Water content [kg·m^{-3}]	Chemical admixture	
		%	silica fume (SF)	fly ash (FA)						%	kg·m^{-3}
			kg·m^{-3}								
M1	450.0		–	–	1 : 0.8	951.0	761.0	0.45	202.0	2	9.0
M2	500.0		–	–	1 : 0.8	885.0	708.0	0.45	225.0	2	10.0
M3	405.0	10	45.0	–	1 : 0.8	951.0	761.0	0.45	202.0	3	13.5
M4	450.0	10	50.0	–	1 : 0.8	885.0	708.0	0.45	225.0	3	15.0
M5	450.0		–	–	1 : 0.8	917.0	734.0	0.5	225.0	2	9.0
M6	450.0		–	–	1 : 1	856.0	856.0	0.45	202.0	2	9.0
M7	450.0		–	–	0.8 : 1	761.0	951.0	0.45	202.0	2	9.0
M8	450.0		–	–	1 : 0.8	951.0	761.0	0.45	202.0	3	13.5
M9	405.0	10	45.0	–	1 : 0.8	951.0	761.0	0.45	202.0	2	9.0
M10	427.5	5	22.5	–	1 : 0.8	951.0	761.0	0.45	202.0	2	9.0
M11	337.5	25	–	112.5	1 : 0.8	951.0	761.0	0.45	202.0	2	9.0
M12	292.5	35	–	157.5	1 : 0.8	951.0	761.0	0.45	202.0	2	9.0

Source: own work.

The behavior of each mix in its fresh condition was assessed directly after the end of mixing using the slump flow, V-funnel and L-box experiments. After that the concrete batch was poured in oiled molds of different test examples created for testing the mechanical characteristics for each mix. The standard cubic test specimens with measurements of 150 × 150 × 150 mm and cylindrical specimens of 150 × 300 mm for the compressive and splitting tension tests were used. Pouring of concrete was carried out in one layer to the top edge of the mold without any compaction or vibration. The excess concrete was scrapped off and the top surface was finished using a trowel. The molds were kept horizontal during and after placing concrete until hardening as shown in Figure 1. After about 24 h the specimens were taken out of the molds and submerged in 25°C pure water until testing.

a b

FIGURE 1. The cubic (a) and cylindrical (b) specimens in the molds
Source: own work.

Results and discussion

Table 2 includes the results of the fresh properties of each SCC combination. Slump-flow, V-funnel, and L-box experiments results are given in Table 2 (Fig. 2). The diameter of the bulk of concrete after it had been released from a standard slump cone was measured in 2 perpendicular directions. This diameter is known as the slump flow. Slump flow measurements of all SCC mixes were acceptable, falling between 600 and 800 mm, which was a sign of good deformability. The flowability (filling ability) of concrete having a nominal maximum size of 20 mm aggregate was assessed using the V-funnel test. It was performed on the mixtures to evaluate their flow rates through small openings without obstacles. In order to estimate the flowability of SCC mixtures in confined spaces, the flow time test was found. The range of 6 to 12 s is considered an appropriate flow period for SCC. The L-box test is a popular technique for assessing how well new concrete passes through crowded steel rebars. The blockage ratio ($BR = H_2/H_1$) should be between 0.8 and 1.0. It is employed to assess the passage skill.

a b c

FIGURE 2. Self-compacting concrete (SCC) mix under the slump-flow diameter (a), V-funnel (b) and L-box tests (c)

Source: own work.

TABLE 2. Rheological and hardened characteristics of SCC mixtures

Mix code	Slump flow test [mm]	V-funnel test [s]	L-box test (ratio)	7-day compressive strength [MPa]	28-day compressive strength [MPa]	56-day compressive strength [MPa]	28-day tensile strength [MPa]
M1	610	7.5	0.81	29.5	39.5	42.0	3.8
M2	570	8.4	0.75	33.0	41.5	45.5	3.9
M3	700	6.5	0.90	32.0	42.5	49.3	4.1
M4	650	6.8	0.85	36.0	45.2	53.7	4.5
M5	680	6.5	0.87	20.4	29.6	33.1	2.7
M6	650	6.5	0.84	19.8	29.4	31.0	2.7
M7	580	10.0	0.73	18.4	26.2	28.1	2.5
M8	720	6.3	0.94	25.3	36.4	39.2	3.4
M9	550	14.0	0.67	36.0	47.3	54.8	4.6
M10	650	6.8	0.84	32.2	43.0	51.3	4.1
M11	670	6.4	0.86	31.0	41.8	53.3	4.1
M12	620	8.0	0.80	34.2	45.1	56.8	4.8

Source: own work.

Table 2 also shows the compressive strength results of the hardened characteristics for all of the mixtures that were tested test at 7 days, 28 days and 56 days and the indirect tension test at 28 days (Fig. 3). Each result was a mean value for 3 tested specimens.

a b

FIGURE 3. Compressive (a) and splitting tensile strength (b) tests of self-compacting concrete (SCC) mix specimens
Source: own work.

Cement content impact on properties of self-compacting concrete

Increasing the cement content from 450 to 500 kg·m^{-3} resulted in a decline in the SCC mix rheological characteristics as shown in Table 2 and Figure 4. A reduction in the slump flow from 610 to 570 mm was obtained. The addition of 10% SF to the SCC mix led to the same trend. There was an increase in the compressive strength of SCC mixes as a consequence of the rise in the cement content from 450 to 500 kg·m^{-3} at 7 days, 28 days, and 56 days as shown in Figure 5. An increase from 39.5 to 41.5 MPa was obtained at 28 days. The same trend was obtained in the splitting tension test after 28 days. The addition of 10% SF to SCC mix led to the same trend. The results here agree with the effect of cement content on the fresh and hardened properties of SCC at normal conditions at an ambient temperature of 25°C. The increase of its content led to a decrease in the rheological properties due to its consumption of a larger amount of the mixing water in surrounding its particles. However, the increase in the cement content resulted in an increase in the compressive and splitting tensile strengths with the formation of more calcium silicate hydrate (CSH) compounds responsible for the strength.

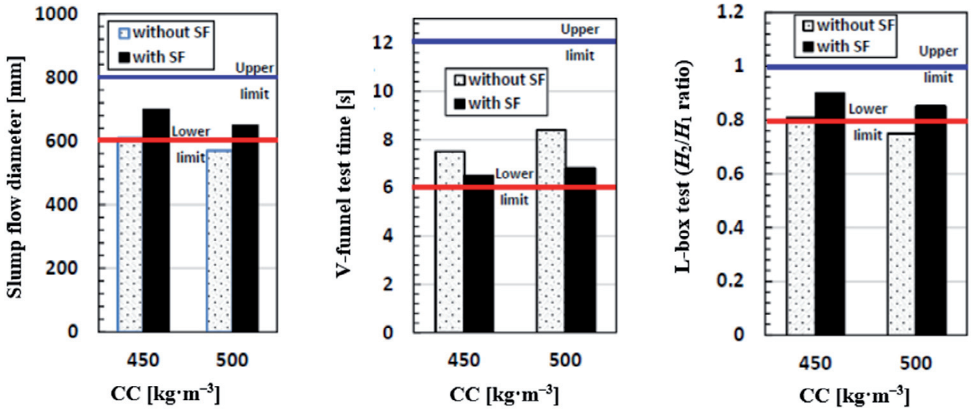

FIGURE 4. Rheological properties for self-compacting concrete (SCC) mixes of various cement contents (cement content – CC, silica fume – SF)

Source: own work.

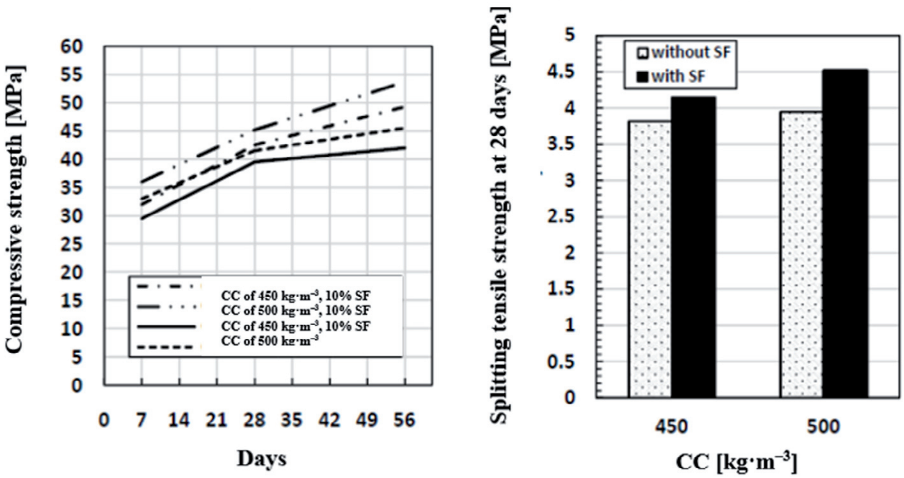

FIGURE 5. Compression and splitting tension test results of self-compacting concrete (SCC) mixes for various test results (cement content – CC, silica fume – SF)

Source: own work.

Water to cement ratio impact on self-compacting concrete properties

The rheological characteristics of the SCC mix increased as a consequence of the rise in water to cement ratio (w/c) from 0.45 to 0.5 kg·m^{-3} as given in Table 2 and Figure 6. The slump flow increased from 610 to 680 mm. As the water to cement ratio increased from 0.45 to 0.5, the compressive strength of SCC mixtures decreased at all ages of 7, 28 and 56 days (Fig. 7). A decrease from 39.5 to 29.6 MPa was obtained at 28 days. The same trend was obtained for the splitting tensile strength at 28 days. This agrees with the role of water in SSC at normal conditions at an ambient temperature of 25°C. The increase in the amount of water increased the rheology of SCC, but it adversely affected the strength of the concrete mix due to the pores resulting from the evaporation of excess water used for rheology.

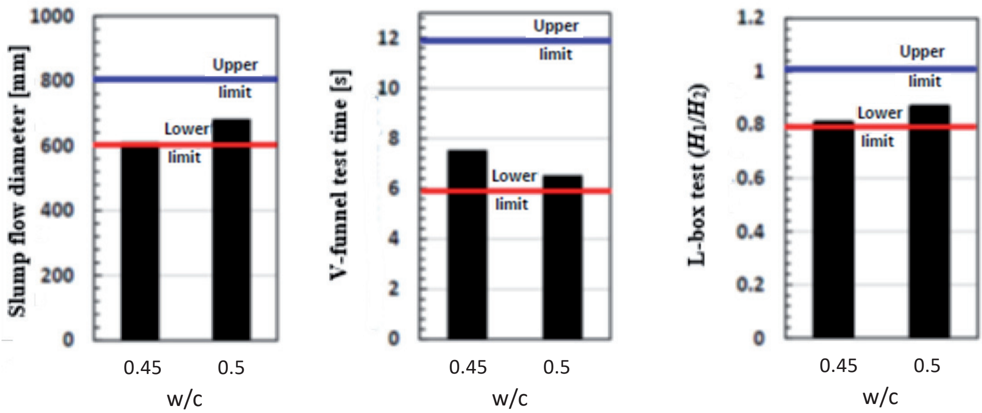

FIGURE 6. Rheological properties for self-compacting concrete (SCC) mixes of various water to cement ratios (w/c)
Source: own work.

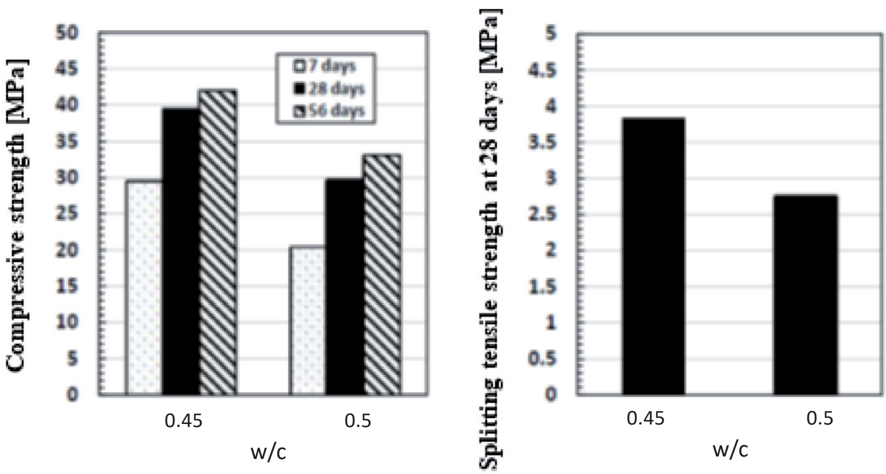

FIGURE 7. Compression and splitting tension test results of self-compacting concrete (SCC) mixes for various water to cement ratios (w/c)
Source: own work.

Coarse to fine aggregate ratio impact on self-compacting concrete properties

The change in the coarse to fine aggregate ratio from 1 : 0.8 (or 1.25 : 1) to 0.8 : 1 resulted in a reduction in the SCC mix rheological characteristics. A reduction in the slump flow from 610 to 580 mm was obtained. However, the ratio of coarse to fine aggregate of 1:1 gave the best rheological properties with a 650 mm slump flow as given in Table 2 and Figure 8. The change of coarse to fine aggregate ratio from 1 : 0.8 (or 1.25 : 1) to 0.8 : 1 through the ratio of 1 : 1 resulted in a decrease in the SCC compressive strength at all ages of 7, 28, and 56 days (Fig. 9). A reduction from 39.5 to 26.2 MPa was obtained at 28 days. The same trend was obtained for the splitting tensile strength at 28 days. This also agrees with the effect of coarse to fine aggregate ratio on the properties of SCC at normal conditions at an ambient temperature of 25°C. It is known that the paste volume fraction is greater in both viscosity modifying admixture and powder-type SCC than in ordinary concrete at the expense of the volume of aggregate, and particularly at the expense of coarse aggregate. This means that the coarse to fine aggregate ratio of SCC is smaller than that of ordinary concrete in order to satisfy the SCC rheological properties; SCC rheological properties are based on low yield stress, moderate viscosity and retention of the kinetic energy of the flowable mix by reducing the volume fraction of coarse aggregate. These measures are required to satisfy the fluidity, resistance and prevention of interparticle collision, and segregation resistance (Bonen & Shah, 2004).

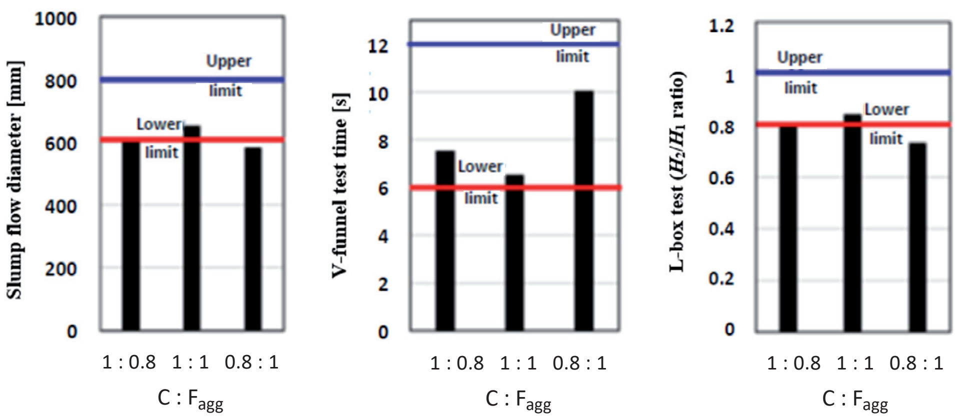

FIGURE 8. Rheological properties for self-compacting concrete (SCC) mixes of different coarse to fine aggregate ratios (C : $_{Fagg.}$)

Source: own work.

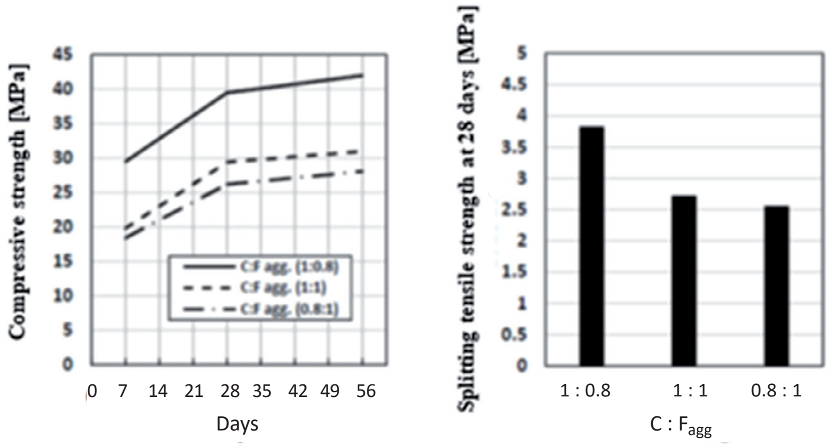

FIGURE 9. Compression and splitting tension test results of self-compacting concrete (SCC) mixes for various coarse to fine aggregate ratios (C : $F_{agg.}$)

Source: own work.

Chemical admixtures impact on self-compacting concrete properties

The increase in the percentage of the high range super plasticizer (SP) added from 2 to 3% by weight of cement led to a rise in the rheological properties of the SCC mixes as shown in Table 2 and Figure 10. The slump flow increased from 610 to 720 mm. The addition of 10% SF to SCC mix led to the same result. The increase in the percentage of the high range super plasticizer from 2 to 3% resulted in

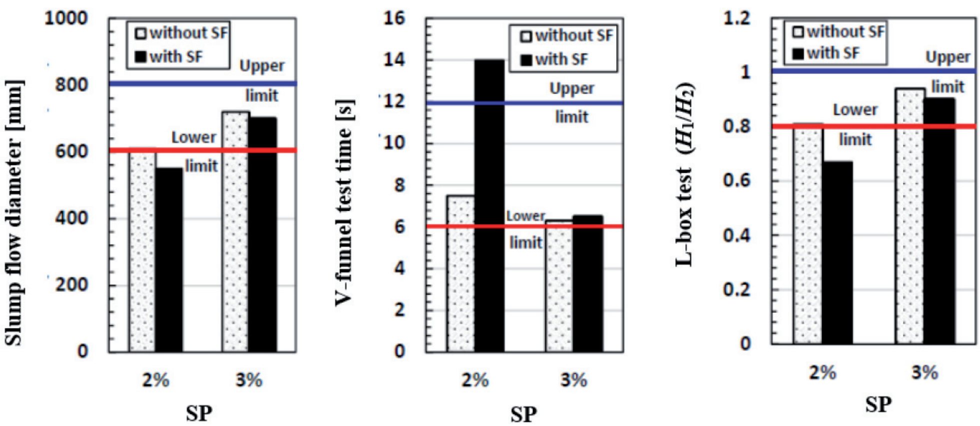

FIGURE 10. Rheological properties for self-compacting concrete (SCC) mixes of different percentages of superplasticizer (SP), (silica fume – SF)

Source: own work.

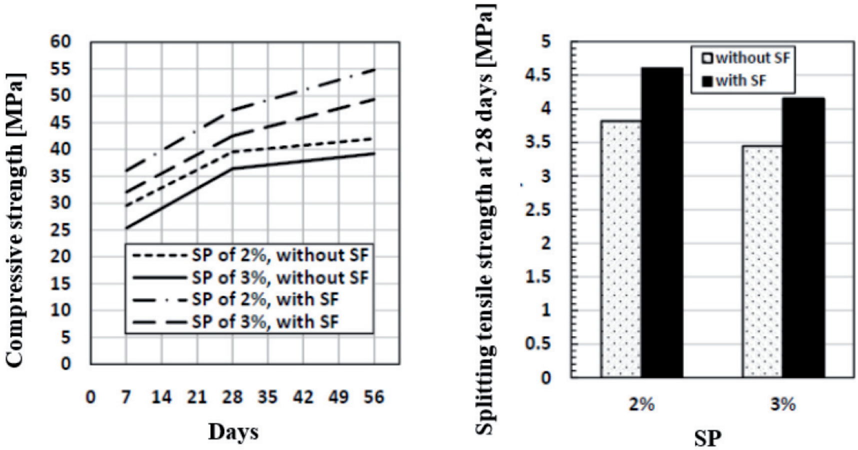

FIGURE 11. Compression and splitting tension test results of self-compacting concrete (SCC) mixes for various percentages of superplasticizer (SP), (silica fume – SF)

Source: own work.

a reduction in the SCC mixes compressive strength at all ages of 7 days, 28 days, and 56 days (Fig. 11). A decrease from 39.5 to 36.4 MPa was obtained at 28 days (7.8% less). The same trend was obtained for the splitting tensile strength after 28 days. The addition of 10% SF to SCC mix led to the same results. This agrees with the role of the high range super plasticizer in SSC at normal conditions at an ambient temperature of 25°C.

Mineral admixtures impact on self-compacting concrete properties

Silica fume impact on self-compacting concrete properties

The rheological characteristics of the SCC mix increased as a result of the addition of 5% silica fume partially replacing a similar amount of cement as shown in Table 2 and Figure 12. The slump flow increased from 610 to 650 mm. The rheological characteristics of the SCC mix decreased and no longer satisfied the rheological limits of the SCC mix as a result of the addition of 10% silica fume partially replacing similar amount of cement. A reduction in the slump flow from 650 to 550 mm was obtained. The compressive strength of the SCC mixes increased at all ages of 7, 28, and 56 days when silica fume was increased from 0% to 5% partially replacing similar amount of cement (Fig. 13). An increase from 39.5 to 43 MPa was obtained at 28 days. The same trend was obtained for the splitting tensile strength after 28 days. The compressive strength of the SCC mixes increased at the same ages when silica fume was increased from 5 to 10% partially replacing similar amount of cement. An increase from 43 to 47.3 MPa was obtained at 28 days. The same trend was obtained for the splitting tensile strength at 28 days. This effect of SF agrees with its effect on SCC at normal conditions at an ambient temperature of 25°C.

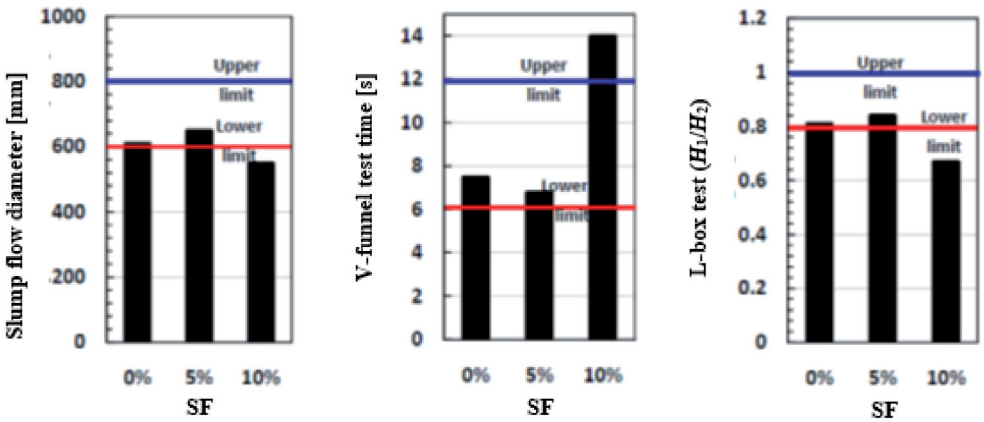

FIGURE 12. Rheological properties for self-compacting concrete (SCC) mixes for various percentages of silica fume (SF)

Source: own work.

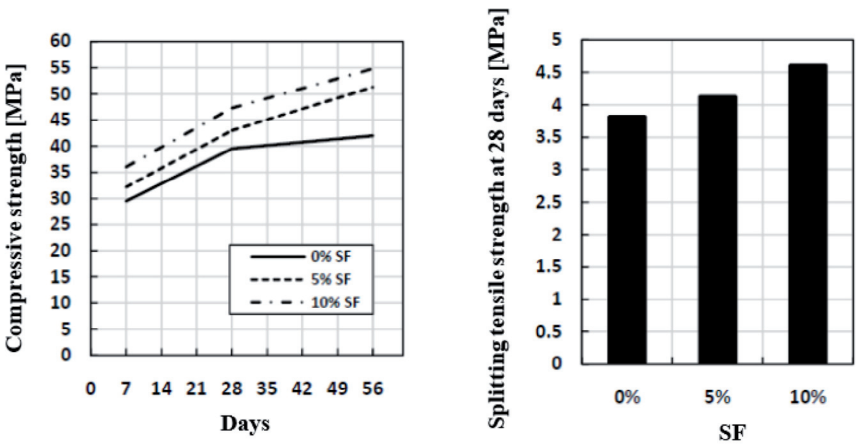

FIGURE 13. Compression and splitting tension test results of self-compacting concrete (SCC) mixes for various percentages of silica fume (SF), (silica fume – SF)

Source: own work.

Fly ash impact on self-compacting concrete properties

The rheological properties of the SCC mix increased as a consequence of the addition of fly ash, which was increased from 0% to 25% as a partial substitute of the weight of cement as shown in Table 2 and Figure 14. The slump flow increased from 610 to 670 mm. The rheological properties of the SCC mix decreased, but still satisfied the rheological limits of the SCC mix as a consequence of the rise in fly ash from 25 to 35% partially replacing a similar amount of cement. A reduction in the slump flow from 670 to 620 mm was obtained.

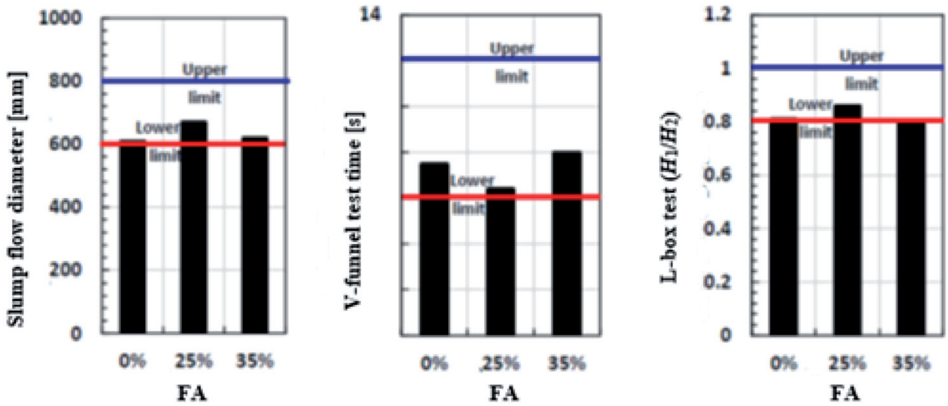

FIGURE 14. Rheological properties for self-compacting concrete (SCC) mixes for various percentages of fly ash (FA)

Source: own work.

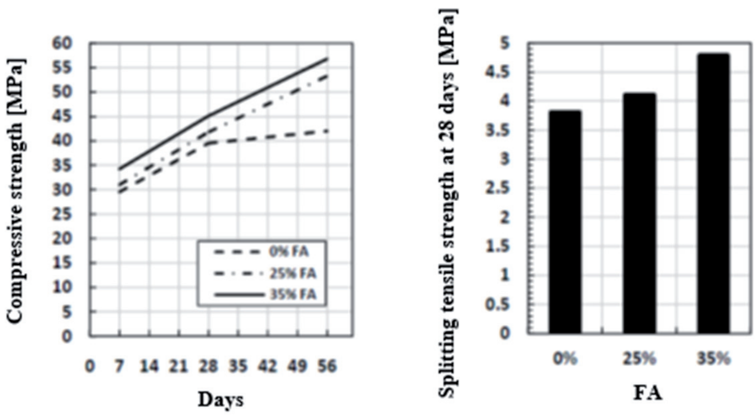

FIGURE 15. Compression and splitting tension test results of self-compacting concrete (SCC) mixes for various percentages of fly ash (FA)

Source: own work.

Khalil, H. S., Abd Elhameid, M. W., Badawy, A. A. (2023). Performance of self-compacting concrete cast in hot weather conditions. *Sci. Rev. Eng. Env. Sci.*, *32* (3), 284–302. DOI 10.22630/srees.4867

The increase in fly ash from 0 to 25% as a partial replacement of the weight of cement resulted in an increase in the compressive strength of the SCC mixes at all ages of 7 days, 28 days and 56 days as shown in Figure 15. An increase from 39.5 to 41.8 MPa was obtained at 28 days. The same trend was obtained for the splitting tensile strength at 28 days. The compressive strength of the SCC mixes increased at the same ages as a result of the addition of fly ash, which was increased from 25 to 35% partially replacing a similar amount of cement. An increase from 41.8 to 45.1 MPa was obtained at 28 days. The same trend was obtained for the splitting tensile strength at 28 days. This effect of FA agrees with its effect on SCC at normal conditions at an ambient temperature of 25°C.

Comparison of fly ash and silica fume's impacts of on self-compacting concrete mixes

The SCC mix with 5% SF gave comparable rheological results to the SCC mix with 25% FA as shown in Table 2 and Figure 16. Both satisfied the rheological SCC limits. The SCC mix with 5% SF showed the marginally increased compressive strength in the SCC mix when compared with that of 25% FA at 7 and 28 days while the latter provided a little bit more compressive strength than the former at 56 days.

The optimum SCC mix constituents from this study which satisfied the SCC rheological limits and produced 52 MPa compressive strength at 56 days was achieved with cementitious content of 450 kg·m^{-3} and a 0.45 water cementitious ratio, 1 : 0.8

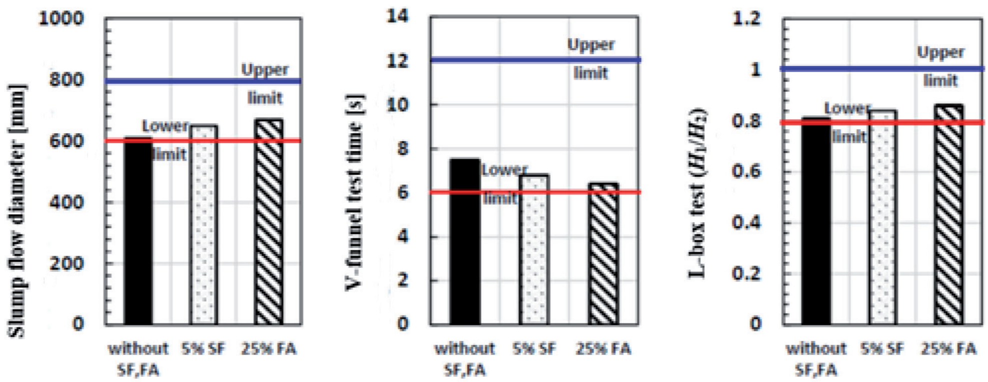

FIGURE 16. Rheological properties for self-compacting concrete (SCC) mixes with different pozzolanic materials (silica fume – SF, ash fly – FA)

Source: own work.

coarse to fine aggregate ratio, 2% high range chemical admixture, either 5% SF or 25% FA mineral admixture as partially replacing similar weight of cement.

However, higher values of compressive and splitting tensile strengths could be obtained with 10% SF or 35% FA contents as a substitute for similar amounts of cement, but without satisfying the lower limits of the rheological characteristics of SCC mixes in case of the former mix with 10% SF or satisfying at about the lower limits in case of the latter mix with 35% FA.

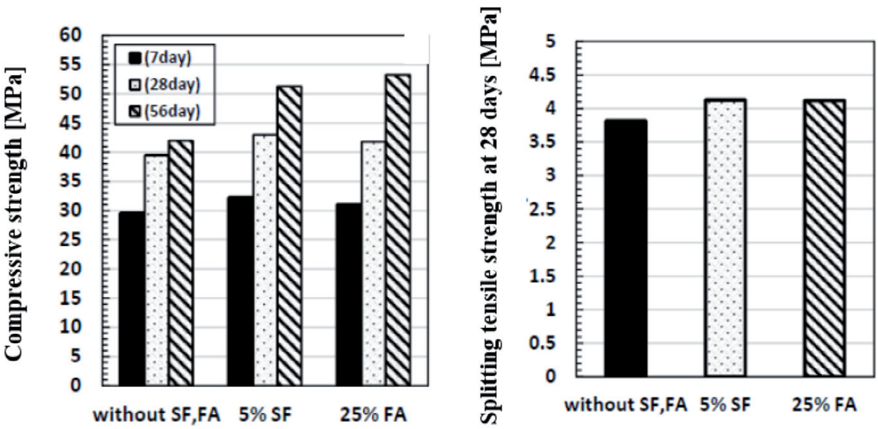

FIGURE 17. Compression and splitting tension test results of self-compacting concrete (SCC) mixes with different pozzolanic materials (silica fume – SF, ash fly – FA)

Source: own work.

Conclusions

It is worth mentioning that this study focused on the production of SCC mix in situ in hot weather conditions at a temperature of about 35°C. It can be concluded within the limits of this study that a properly proportioned SCC mix can perform well under such conditions. The impact of SCC mix ingredients on the rheological and hardened properties of the mix under such conditions was similar to their impact under normal conditions at 25°C and as follows:

1) It was found that the SCC mix rheological properties increased with decreasing the cement content, increasing w/c ratio, decreasing $C : F_{agg.}$ ratio to a certain extent, increasing the high range superplasticizer, increasing FA content and increasing SF but up to 5% after which a decrease in the rheological properties occurred.

2) Compressive and splitting tensile strengths of the SCC mixes increased as the cement content of the SCC mixes rose, the w/c ratio decreased and, the C : $F_{agg.}$ ratio increased, the high range super plasticizer decreased and the SF or FA increased as a substitute for a similar amount of cement.
3) Optimum values were obtained for these ingredients, which satisfied the SCC rheological characteristics of the mix and gave a compressive strength of about 42 MPa at 28 days and about 52 MPa at 56 days.
4) These optimum constituent values were 450 $kg \cdot m^{-3}$ of cement, 0.45 water cementitious ratio, and a coarse to fine material ratio of 1 : 0.8, a high range superplasticizer of 2%, and a mineral admixture of either 5% SF or 25% FA as a substitute for a similar amount cement.
5) Higher strengths were obtained using 10% SF or 35% FA while satisfying the rheological characteristics of the SCC mixes only in the case of using 35% FA.

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Summary

Performance of self-compacting concrete cast in hot weather conditions. This work focused on how self-compacting concrete (SCC) performs in situ in hot weather conditions at an ambient temperature of about 35°C. Tests for the rheological properties and compressive and splitting tensile strength aspects were carried out. The results of SCC mix ingredients on the rheological and hardened features of SCC mix were studied. Variations in the amount of portland cement content (CC), water to cement ratio (w/c), coarse to fine aggregate ratio (C : F), chemical admixture ratio, and pozzolanic admixture ratio were considered. Optimum values were obtained for these ingredients, which satisfied the SCC rheological characteristics and gave a 28-day compressive strength of 42 MPa, and 52 MPa after 28 days and 56 days, respectively. These optimum constituent values were 450 $kg \cdot m^{-3}$ of cement, 0.45 water cementitious ratio, and a coarse to fine material ratio of 1 : 0.8, a high range superplasticizer of 2%, and a mineral admixture of either 5% silica fume or 25% fly ash as a substitute for a similar amount cement.

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