APPLYING GAME THEORY TO WATER MANAGEMENT USING CONSTRUCTED FLOATING WETLANDS: KALLYANPUR DETENTION POND STUDY

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ABSTRACT

Constructed Floating Wetlands (CFWs) are considered a sustainable, nature-based solution to improve water quality, offering both ecological and aesthetic benefits. The game theory (prisoner's dilemma) approach will be used to understand stakeholder dynamics in water management with CFWs for the detention pond in Kallyanpur governed by DNCC (Dhaka North City Corporation). We would identify a Nash Equilibrium within our game theory framework by analyzing water quality data and stakeholder interactions. This would highlight strategies aligning with stakeholder interests to enhance water quality and optimal strategy for local communities, government bodies, and the wetland system. A theoretical framework of linear programming has been used for running the model in MATLAB, and the goal is to maximize each of the stakeholders' net benefits. The findings here would provide insights into maximizing the potential of CFWs for water quality improvement and provide guidelines for policy implementations that can ensure the long-term success and viability of such initiatives. In this analysis, DNCC consistently encountered obstacles in numerous scenarios, primarily related to cost management and project execution. In contrast, the local and squatter communities saw a mix of advantages and disadvantages. The Nash equilibrium emerged in the ninth scenario, where all parties saw benefits, underscoring the importance of well-balanced approaches for mutual gains in community and urban development initiatives.

Keywords: *Constructed Floating Wetlands, Water Quality Management, Game Theory, Stakeholder Dynamics, Nash equilibrium*

1. INTRODUCTION

As our world is heading towards a rapid economic advancement along with its increasing population, water scarcity and water contamination have emerged as common challenges in recent times (Hoekstra and Mekonnen, 2012). Rivers, which are our primary sources of surface water, are now subject to a complex interplay of anthropogenic activities and natural influences. Since river water quality is also another key criteria of managing aquatic environment, precise assessments of water quality are needed to provide significant insights for decision-makers in the policy-making and a sustainable way of management for water resources (Yun et al., 2009).

Historically, since the industrial revolution, untreated wastewater discharge has been a problem for developing nations (Hostetter, 2006). While the developing countries with higher economic income in North America and Europe process 70% of their wastewater before to release, just 8% and 28% of wastewater is being treated in the low and lower-middle-economic mostly in the Asian region which pose a serious threat to urban river pollution (Kookana et al., 2020; UNEP, 2016). Sustainable Development Goal (SDG) objective 6.3 states that by 2030, water quality should be improved by cutting down on pollution, banning dumping, minimising the discharge of hazardous materials and chemicals, halving the amount of wastewater that is left untreated, and significantly expanding safe reuse and recycling throughout the world. Therefore, these efforts must balance social, political, and economic trade-offs in order to reverse the degradation of environment, encourage economic expansion while lowering pollution exposure among the populace (UN General Assembly, 2015).

With approximately 17 million residents, Dhaka is considered as one of the developing world's rapid-growing cities. It is surrounded by linked river systems that facilitate trade, transportation, and stormwater drainage. However, due to the untreated discharge of sewage and other types of untreated wastewater, the water quality of Dhaka's surrounding rivers has deteriorated significantly over the past three decades. It is an irony that merely 20% of Dhaka city has access to a sewer network, while 1,250 million litres of sewage are dumped into rivers daily without any proper treatment or calculative measures. It's needless to mention that the river water quality is atrocious, with 30-40% of the pollution coming from domestic waste, which puts the rivers in their death throes (The Business Standard, 2023).

There are several factors and reasons for the deterioration of surface water quality, and nutrient pollution is one of them. This type of pollution mainly arises from stormwater runoff in urban areas, which carries a variety of pollutants including rainfall, fertilizers, atmospheric particulates, street debris, and soil erosion, directly into surface water sewers (Novotny and Olem, 1994). Department of Environment (DoE) has classified four rivers that round Dhaka as environmentally sensitive regions in 2009 due to the extreme pollution (The Daily Star, 2009). In 2015, the Planning Commission ruled that these rivers were unsuited for any kind of human usage as well (General Economics Division 2015, p. 423). What's more, since groundwater currently supplies 87% of the city's increasing water demand, the contamination also has significant effects on this source, posing a threat of pollution.

The absence of effective stormwater treatment can lead to severe consequences, including human and animal toxicity through consumption, unsightly algal blooms, oxygen shortages impacting marine ecosystem, and smells from degrading organic substances (Tarazona et al., 2008). Developed countries have introduced wet detention ponds to tackle challenges which arises due to the problems related to stormwater management. For instance, wet detention ponds are among the favoured Best Management Practices (BMPs) in Florida, particularly for stormwater management. These ponds tackle stormwater's volume and quality by holding runoff during storms and purifying it through a combination of chemical, biological and physical processes (USEPA, 1999). Excess nutrients like phosphorus (P) and nitrogen (N) are carried into these waterbodies via surface movement, raising issues like eutrophication of surface water and contamination of ground and spring water, especially during these weather events. Such scenarios can lead to excessive algae and invasive plant growth, negatively impacting ecosystems.

Although retention basins have been considered as one of the most popular options in stormwater management, they show limited effectiveness against dissolved contaminants, mainly removing larger, particulate-bound pollutants. Conversely, wetland vegetation is known for eliminating finer particles or soluble pollutants (Bavor et al., 2001). It is also worthy to mention that when a pond retrofit with a Floating Treatment Wetlands (FTWs), the water treatment efficiency shows a better result than a traditional retention pond (Karine et al., 2013). Therefore, for a more innovative and green design, along with a better management practice, Floating Treatment Wetlands (FTW) can be worthy to solve the water pollution problem. Water quality management experts find FTWs to be an appealing alternative due to their necessity for smaller areas and aesthetic benefits. The plants which float on the wetlands may immediately absorb nutrients into their biomass due to the creation of perfect root-zone habitat for microorganisms (Billore et al., 2008).

Over the past 20 years, artificially produced wetlands have gained widespread acceptance as a stormwater treatment alternative for urban areas, and they have been included in urban design plans, particularly in areas facing water issues (Weiss et al., 2007). Their popularity is mainly because of their low-maintenance and simple operational nature (Lee and Li, 2009). Constructed Floating Wetlands (CFWs) also have been the subject of increased attention in recent years for their effectiveness in purifying storm water runoff in urban areas (Borne et al., 2013).

Despite a handful of research being conducted on pollution sources and water treatment technologies for urban water systems, little has been done to address the differences in exposure among different stakeholders and socioeconomic groups. Poor visual amenities, offensive smells, a lack of recreational activities, and the stigmatization of communities all have broader effects on the well-being of those who live close to polluted zones like squatting communities (Damery et al., 2008). However, managing squatter communities is one of the toughest tasks in Bangladesh, aside from pollution management. Typically, workers' families live in low-income residential areas, or slums, that are frequently scattered throughout Dhaka's industrial clusters. Slums, where 35 percent of Bangladesh's urban people live, have inadequate water and sanitation systems (Vlahov et al., 2005). Non-governmental organisations (NGOs) and Dhaka Water Supply & Sewerage Authority (DWASA) erected around 27% and 21% of the waterpoints in big slums situated on government-owned territory, respectively.

According to the United Nations Department of Economic and Social Affairs, the latest estimates for July 2023 to July 2024 were updated on July, 2023 where they state that The population density in Bangladesh is 1329 per Km^2, which is one of the highest population density in the world. Therefore, it also indicates that we face an acute challenge in land availability for housing. The country's constitution highlights housing as a fundamental need, placing a constitutional mandate on the government to ensure housing rights. Moreover, These low-income inhabitants shoulder a big chunk of the price of pollution to the environment. Children under the age of five who lived in densely populated slums were far more likely than those who did not to have severe dehydration and diarrheal illnesses caused by Vibrio cholerae (Ferdous et al., 2014). The escalating demand for water and limited freshwater resources have led to conflicts among water user groups with differing needs and priorities. These disputes are particularly evident in projects such as interbasin water transfer, whose goals range from increasing water supply for users (enhancing the satisfactory level and economic benefits) to minimizing environmental impacts. Therefore, various strategies have been proposed to balance these objectives and distribute water equitably among diverse stakeholders in interbasin water allocation challenges. And among the strategies, Game Theory has been a successful strategy in resolving the conflicts through a win-win approach.

Game Theory is a mathematical framework that has been used to study and analyse strategic interactions and decision-making among rational players or stakeholders. These stakeholders can be individuals, organizations, or countries as well. With this game theory tool, we can hindcast how a stakeholder can act and react in order to keep a winning position for himself and also for the other stakeholders. Hence this is an approach that is used in order to diminish conflicts and to make better policies in a more mathematical and calculative manner. According to this framework, every stakeholder are players here who make their decisions based on their own objectives. Here, they attempt to outwit other players in a conventional game by guessing the next move each other will make. The decisions made by the players determine how the game is concluded. Usually, the concept of Nash equilibrium, where each player's plan is optimum given the other player's strategy, is illustrated through the Prisoner's Dilemma. Prisoner’s Dilemma is a fundamental concept in game theory and it is being used as applications in various real-world scenarios, such as economics, business, international relations, and social decision-making to analyse situations where individual incentives may lead to collectively undesirable outcomes.

Game Theory has seen various applications in water resource management. Multiple cooperative game theories were used by Tisdell and Harrison (1992) to distribute water across farms in Queensland, Australia, in an efficient and equitable manner. Through trade among six sample farms, the study assessed the distributive effects of four allocation techniques both with and without consumptive usage. They evaluated the relative fairness of various allocation techniques using the Rawlsian criteria of social justice which was useful for policy evaluation in water allocation management. The results of cooperative and noncooperative strategies in the Israeli-Palestinian dispute over regional aquifers were examined (Netanyahu et al., 1998). Luss (1999) conducted research on a range of resource allocation problems and showed the value of the Lexicographic Minimax technique in achieving equitable and optimum resource distribution. Then there are Leoneti and Pires (2017a), who conducted research on water resource management from the perspective of decision sciences by reviewing the literature.

In our study, we present the first game theory framework by analysing water quality data and stakeholder interactions for a stormwater detention pond. This would emphasise the best course of action for regional communities, governmental organisations, and the wetland system, as well as tactics that support stakeholder interests in improving the quality of the water. The model has been run in MATLAB using a theoretical framework of linear programming, with the objective being to maximise the net benefits to each stakeholder. The results of this study will shed light on how to best utilise CFWs to enhance water quality and offer recommendations for enacting policies that will support these programmes' long-term viability and effectiveness. The optimal situation where all parties benefited was found using the Nash equilibrium method, highlighting the significance of well-balanced strategies for gains in community and urban development projects.

1.1 Study Area

The study area is located at Kallyanpur, the Northern part of Dhaka city, and falls under Drainage Zone H, about 17.60 km^2. About 9.91 million people in Dhaka City are indirectly benefited by the drainage system improvement due to the detention pond and stormwater pumping system. The detention pond's latitude and longitude are 23.772072° N and 90.345178° E, respectively. One part of this detention pond is connected to Kallyanpur Khal, and its outlet is connected to the Buriganga River.

The Kallyanpur Pumping Station in the project is constructed to improve drainage conditions by maintaining the water level in the regulating pond of Drainage Zone H. According to the design criteria, it has a pumping capacity of 20 m^3/s and a regulating capacity of 2,000,000 m^3.

Figure 1: Location of Study Area

2. METHODOLOGY

The main finding of this study is to maximize the potential of CFWs for improving water quality and to provide suggestions for policy implementation. To execute the game, game theory models require specified components. These models are founded on the assumption that each person or group is attempting to maximize their payoff, which is the utility or benefit they obtain from a particular event. Respondents/players, tactics, payout, data, result, and equilibrium are the six components of the model. The game's regulators are known as RSPD, and the game's outcomes are known as OE (Rahman et al., 2023; Rogers, 1969). The acronym RSPDOE is used, which stands for:

Respondents/Players: The individuals or groups who make game decisions.

Strategies: The various options available to each player.

Payoff: The utility or benefit received by each player because of a certain event.

Data: Information about the game and the other players that each player has.

Outcome: The game is determined by the strategy taken by all players.

Equilibrium: A stable state of the game in which no participant can improve their payoff by altering their approach unilaterally.

For this study, we developed a methodology to run the game. A theoretical framework of linear programming has been employed for the model, with the acknowledgment that political effects or difficulties were not considered. The environmental and the financial impact of the system was also partially disregarded due to a lack of research and data. The objective of the linear programming used with this approach is to maximize the net benefits for each of the three respondents. This paper also provides an example of formulation for multiplayer games along with a method for future solutions.

Based on the reward matrix approach, equilibria of mixed strategies can be identified. Designed to handle multiplayer games, it can address the computational bottleneck of multiplayer equilibria. The study's methodology is illustrated schematically in Figure 2.

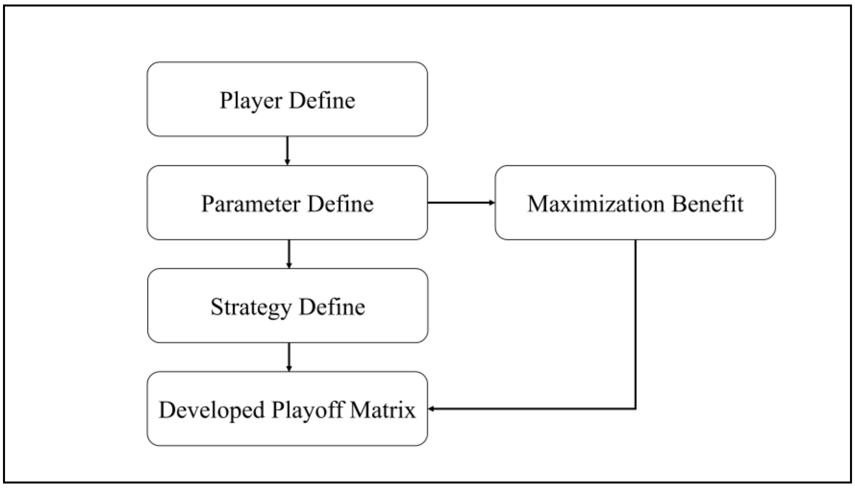

Figure 2: Methodology Flow Chart

2.1 Players Define

To execute the game theory model, it is essential to define the players, and in this study, three distinct players have been identified. The first player is Dhaka North City Corporation (DNCC), which is a municipal government agency responsible for overseeing various administrative and civic duties in the northern part of the capital of Bangladesh. Next, the local community residing around the detention pond, characterized by land ownership and adherence to all laws and regulations enforced by the authority, is considered the second player, and it was defined as the 'Local Community' in this game. Lastly, the third player is squatter groups that appropriated land without authorization, and we defined them as "Squatter Communities".

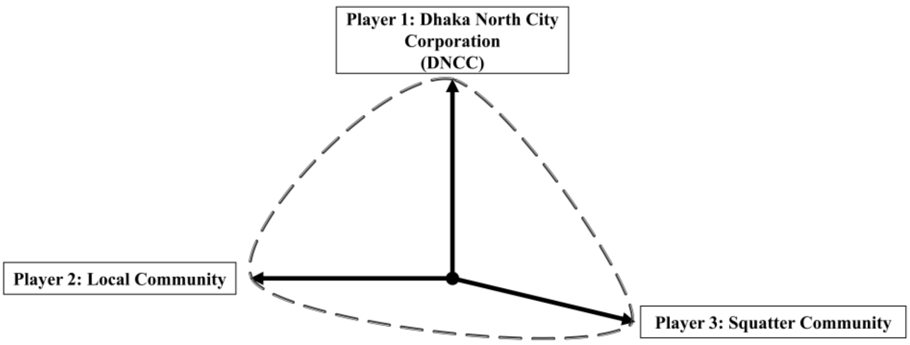

Figure 3: Interactions between players

2.2 Terminology

The game theory model requires certain parameters to run appropriately. The terminology used in this game model is provided below:

F1 = Cost function of land and wetland management
F2 = Cost function of water quality management
F3 = Cost function of submerged embankment
F4 = Cost function of rehabilitation
U1 = Utility function of land and wetland management (detention purpose)
U2 = Utility function of water quality management
U3 = Utility function of submerged embankment
U4 = Utility function of strategy buildup and policy implementation
U4 = Utility function of strategy buildup and policy implementation
U5 = Utility function of treated water (efficiency, cost & environment stability)
U6 = Utility function of socio-economic perspective

In this analysis, different factors include various elements. The land and wetland management cost function (F1) comprises two elements: the cost of land maintenance and the cost of wetland maintenance. Similarly, the water quality management cost function (F2) includes the cost of maintaining water quality in wetlands and the cost of floating mat. The data for this study were gathered from Dhaka North City Corporation (DNCC) and the government's annual report. All parameters share the same unit in taka, which has been converted into dollars and further transformed into dollar rates, represented as numerical values between 0 to 1 for better comprehension.

2.3 Maximize Benefit

The goal of this game is to determine the maximized benefits for every player using different strategies. The maximized benefit can be represented using the following equation:

$$\text{Maximize Benefit, } M = U1 + U2 + U3 + U4 + U5 + U6 - F1 - F2 - F3 - F4$$

2.4 Strategies of Players

In game theory, "strategy" refers to a comprehensive plan of action that a player employs to attain their goals considering the actions and reactions of other players in the game. Players' strategies determine their decisions or moves at each stage of the game (Rogers, 1969). In this study, we defined three specific strategies for every player. They are:

1. Present State
2. Project Implementation Period
3. After Project Implementation Period

3. RESULTS & DISCUSSIONS

Table 1 represents the findings from the bar theory game model's linear programming techniques for this study. As we start this game model, we first establish the identities of all players and decide on the factors that will control the game. We then use a linear programming model to run the game and determine every feasible result given the given scenario. The key to this strategy is to frame the game as a linear optimization problem, in which the main goal is to maximize the payoff of one player while decreasing the payoff of the other.

Table 1: Payoff Matrix based on different scenario for every players.

Player		Local Community (P2) & Squatter Community (P3)		
	Strategy	**Present State**	**Project Implementation Period**	**After Project Implementation**
DNCC (P1)	**Present State**	-0.2, -0.2, 0.2	-0.2, -0.1, -0.3	-0.2 0, 0.6, 0.2
	Project Implementation Period	-0.4, -0.2, 0.2	-0.4, -0.1, -0.3	-0.4, 0.6, 0.2
	After Project Implementation	0.6, -0.2, 0.2	0.6, -0.1, -0.3	0.6, 0.6, 0.2

The first step in turning the game into a linear program is to define the decision variables. These variables stand for the odds that each player will choose their own strategy in the context of a zero-sum game. We may build the objective function and establish the constraints for the linear program when these choice variables are created. The goal of the linear programming model is to maximize gains for a player, and the objective function simply expresses this payoff.

We find some negative values in this game theory model that depend on the maximize equation. However, the terminology we used for this game theory established how to maximize benefit. Positive values typically indicate favourable outcomes for all players, while negative values suggest unfavourable circumstances for players in the game.

3.1 Strategy Investigation

In our study, each player has three identical strategies in game theory, which may or may not be effective for them. While some strategies might be crucial, others might work better for specific players. Firstly, for the "Present State" scenario, DNCC and the local community find themselves in critical situations. Although the local community pays taxes to DNCC so that they can maintain their normal way of life, it cannot be possible for squatter communities. However, the squatter community finds this situation favourable as they do not need to pay taxes to DNCC or any household fees to any proper organization. Secondly, during the "Project Implementation Period," the intense construction work causes issues for all the players. Although the squatters are temporarily removed from their homes by the authorities, the DNCC is required to oversee every detail and bear the heavy construction costs. Aside from the construction, the local community also has some issues. Finally, each player discovers a workable solution during the "After Project Implementation" phase, in which the local community will be able to live in a better environment, the squatter community will be able to find a safe place to live, and DNCC will be able to collect more taxes from the project area.

In this game theory, we identified nine cases, each representing the payoff of three players in different strategies. These cases helped us determine the Nash equilibrium of the game theory. The first case portrays the present state for three players, with only the squatter community deriving benefits. On the other hand, in this initial scenario, the local community faced issues during certain months of the year due to waterlogging and untreated water. DNCC has also encountered similar problems related to the maintenance of stormwater in the northern part in this particular scenario.

The second case represents the present state of DNCC and the project implementation period for local and squatter communities. In this scenario, every player will suffer a lot because of maintaining cost management. DNCC has suffered a lot in this stage because they need to implement a cost budget from their fund. On the other hand, local communities will face socioeconomic problems as their large-scale construction is ongoing. Squatter communities need to escape this area due to high regulation so they need to find an alternative solution which will create a cost management problem.

The third case represents the present state of DNCC and after project implementation of the other two players. In this case, DNCC will face loss but the other two players will gain benefit because of the implementation of the project. In the fourth, fifth, and sixth case scenarios, DNCC will suffer every scenario because of their action. The local community and squatter community both will benefit in the sixth case which is after the project. In the seventh, eighth, and ninth cases, DNCC will benefit in every case whereas the other two players will be benefited in the ninth scenario. Therefore, the ninth case turns out to be the Nash equilibrium of this game model.

4. CONCLUSIONS

This research offers valuable insights into the interactions between the squatter community, the local community, and the Dhaka North City Corporation (DNCC) through a game theory lens. We investigated nine different scenarios to identify the Nash equilibrium, observing how each scenario affected the stakeholders differently, with the benefits and challenges changing as the project progressed. It was seen that while DNCC faced consistent challenges across several scenarios, particularly in terms of cost management and project implementation, the local and squatter communities experienced both benefits and setbacks. Therefore, identifying the Nash equilibrium was essential to determine the most beneficial scenario for this water quality management project, as the Nash equilibrium is defined by each player making their optimal decision while considering the others' choices. Here, Nash equilibrium was identified in the ninth case, where all players benefited, highlighting the significance of balanced strategies in achieving mutual gains in community and urban development projects. It's noteworthy to mention that Nash equilibrium is not about reaching the best possible scenario in an absolute sense, but rather about reaching the best outcome given the strategic interaction between players.

This study, however, has limitations due to using cost and utility function data from a specific year. We only used financial and benefit data from one year, which means our results might not apply in other times or situations, and this should be kept in mind for any future research. Also, due to time constraints, the inclusion of the views of city officials and local people was not covered in this research, although it is important to get a complete picture. As the research is still ongoing, we recommend to hold Focus Group Discussions (FGD) and interview relevant officials through Key Informant Interviews (KII) in the future to gain insight into the perspectives of the people.

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