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Urban Water Supply Planning and Management via an Integrated P-graph-Analytic Hierarchy Process Framework

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Water security is one of the pressing challenges in sustainable cities of the future as the demand for freshwater increases along with the environmental stresses caused by climate change. For example, Metro Manila, Philippines, experienced a water crisis brought by increasing demand and lasting impacts of climate change in 2019. In response, the Metropolitan Waterworks and Sewerage System (MWSS), together with its water concessionaires, Maynilad Water Services, Inc. (Maynilad), and Manila Water Company, Inc. (Manila Water), laid out a water infrastructure plan to bridge the water deficit. However, the decision-making process can be iterative and participatory characterized by uncertainty. This study thus proposed decision-making framework to explore the possibility of alternative sustainable water supply networks in Metro Manila through P-graph and analytic hierarchy process (AHP). Alternatives considered were saltwater desalination, rainwater harvesting, and non-revenue water (NRW) recovery. A sustainable network was defined as having low operational (OPEX) and capital expenses (CAPEX), high water security, and low global warming potential (GWP). Relative weights of sustainability, derived through AHP, showed that water security was the most important sustainability criterion among the surveyed experts in water supply construction and operations. P-graph simulations yielded optimal and near-optimal solutions indicating the possibility of not including the controversial water supply infrastructure project (Kaliwa dam) as a prioritized management option. Instead, sustainable supply networks relied on desalination, rainwater harvesting, and NRW recovery are identified as the main components of the optimal water supply network. Overall, the study suggests that better planning and accounting for sustainability is needed to identify and implement projects that do not only serve the short-term needs but also integrate well into the long-term plans.

1. Introduction

Water security is one of the issues that impede sustainability of cities. In Metro Manila, the Angat dam in Norzagaray, Bulacan, is currently the only freshwater source of potable water, supplying 97 %, or about 4,000,000 m^3/d, to the entire region. This is shared by the two concessionaires, Maynilad and Manila Water, in a 60 - 40 split (MWSS, 2016). The dependency of water supply on Angat dam, the increasing water demand, and the effects of climate change became more apparent in 2019 when large parts of Metro Manila experienced one of the worst water crises when the water level in Angat dam reached its lowest level in two decades (Wateroam, 2020). MWSS released an updated water source map which enumerated additional projects to meet the demand requirements until 2037. These new projects include building new dams, water treatment plants in the Rizal province, and desalination plants around Laguna Lake. The construction of new dams, especially Kaliwa dam, however, raises concerns on the potential negative impact to the indigenous peoples and the ecosystem (Sarao, 2021). The cost of building and operating these infrastructures can increase the water tariffs further. There is an impetus to look for alternative solutions that are less intrusive and more economical while providing adequate water supply. Several alternatives are being explored which include rainwater harvesting, non-revenue water (NRW) recovery, and seawater desalination (Necesito et al., 2013).
Rainwater harvesting can serve as an alternative source of raw water in addition to mitigating the effects of flooding (Necesito et al., 2013). Considering only households in Metro Manila with minimum property size of 50 m^2 can afford rainwater harvesting, an additional 255,000 m^3/d of water can be added to the supply. NRW of

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Manila Water and Maynilad are 12 % and 31 % (MWSS, 2016). According to Frauendorfer and Liemberger (2010), 20 % NRW is the world standard. NRW recovery can only be an option for Maynilad. Seawater desalination plants can draw water from Manila Bay. Though, the water supply volume is potentially unlimited, desalination pose challenges due to the high energy costs.

2. P-graph and Analytical Hierarchy Process (AHP)

P-graph is a tool, developed by Friedler in 1979, that solves Process Network Synthesis (PNS) problems. Unlike mathematical programming, P-graphs generate visual representation of networks and generates superstructures and sub-optimal structures. (Aviso et al., 2019). P-graphs have been widely applied in designing supply chains, especially in the energy-water-food nexus (Heckl et al., 2015). P-graph studies involving water are currently used in industrial setting (How et al., 2021) while studies in urban metabolism are mostly in energy planning (Walmsley et al., 2017). The application of P-graph in regional urban water network study is novel.
AHP, a multiple criteria decision analysis (MCDA) tool developed by Saaty in 1980, forms decision-making in a systematic approach. AHP can process both quantitative and qualitative inputs. AHP integrates the inherent subjectivity of decision preferences into a rigorous mathematical framework (Promentilla et al., 2018). Integrating P-graph and AHP can be used to assess the overall sustainability of process networks.
This study explores a decision-making framework to explore the possibility of alternative sustainable water supply networks in Metro Manila, particularly rainwater harvesting, NRW recovery, and seawater desalination, through P-graph and AHP. The system boundary of the study included the water supply chain, excluding water distribution systems. To achieve the aim, P-graph was used to determine optimal and suboptimal structures of the water network. AHP was used to assess the environmental, economic, and social impacts of the chosen networks and was complemented by interview with key experts.

3. Methodology

The approach taken in this study is summarized in these steps: mapping of existing and planned water treatment plants (WTP) supplying to the concession areas, setting the scenarios and conditions for the P-graph model, simulating the P-graph and integrating AHP to get optimal network.

3.1 Mapping of existing and planned water treatment plants

There are currently 10 WTP supplying water to Metro Manila – five operated by Maynilad and five operated by Manila Water, providing 4,631,000 m^3/d of water. There are three treatment plants currently under construction – one by Maynilad and two by Manila Water (MWSS, 2022), adding 230,000 m^3/d of water to a total water supply to 4,861,000 m^3/d. Additional WTP projects have been identified based on the water security road map of MWSS as shown in Figure 1.

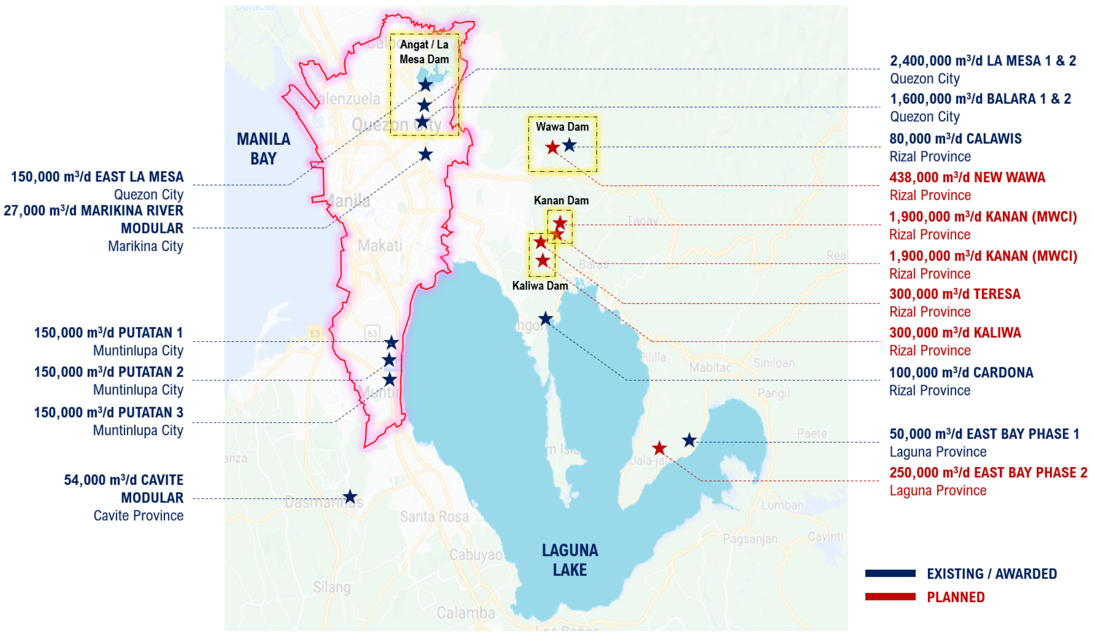

Figure 1: Metro Manila Water Supply roadmap (MWSS, 2022)

3.2 Building scenarios

The actual production will heavily depend on the raw water volume coming in. During the summer season, water level in Angat dam can drop especially during prolonged periods of drought caused by the El Niño phenomenon (MWSS, 2016). In Laguna Lake, the reduced rainwater causes more polluted seawater from Manila Bay to enter increasing the salinity of the water which reduces the efficiency of the reverse osmosis membranes. Seasonal algal blooms can block the intake structure further reducing the volume of water that can be treated. The continuous outpour can disturb the sediments in the water sources causing turbidity to increase beyond capacity, forcing them to operate at reduced levels to maintain the water quality (Baclig, 2022).
Table 1 shows the four different scenarios considered in the modelling. In the normal case, all the WTP are producing at 100 % capacity. In crisis case, all the treatment plants are assumed to be producing 15 % less to account for the disruption events, while the demand is also 15 % higher. MWSS (2016) set 15 % as supply and demand buffer in the data projection and hence seems to be a reasonable value for this study.

Table 1: Scenarios considered in the modelling

No.	Scenario	Normal case	Crisis case
1	With alternatives	100 % demand / 100 % supply	-
2		-	115 % demand / 85 % supply
3	With no alternatives	100 % demand / 100 % supply	-
4		-	115 % demand / 85 % supply

3.3 Simulating P-graph

Sustainability dimensions used in the modelling include CAPEX & OPEX for economy, global warming potential (GWP) contribution for environment, and overall water supply for society. Table 2 summarizes the economic and social data gathered, most of which come from the government (MWSS). For treatment plants that are either already operational or are under construction, only the operating cost was considered. For projects that are yet to be implemented, both the investment and operating costs were considered. Alternative solutions including rainwater harvesting, non-revenue water reduction, and seawater desalination were included as water sources. The projected water demand of Metro Manila in 2037 was used as P-graph product (MWSS, 2016).

Table 2: Summary of values used in the P-graph modelling

Source	Treatment Plant	Capacity		CAPEX (Philippine Peso, PHP)	OPEX (PHP/m^3)	Reference
		Normal	Crisis			
Angat dam	La Mesa 1 & 2	2,400	2,040	-	5.7	MWSS, 2016
	Balara 1 & 2	1,600	1,360	-	5.7	MWSS, 2016
	East La Mesa	150	127.5	-	5.7	MWSS, 2016
Laguna Lake	Putatan 1, 2, & 3	400	340	-	22.8	MWSS, 2016; Pearson et al., 2021
	Cardona	100	85	-	22.8	MWSS, 2016; Pearson et al., 2021
	East Bay 1	50	42.5	-	22.8	MWSS, 2016; Pearson et al., 2021
	East Bay 2	250	212.5	19 x 10^9	22.8	MWSS, 2016; Pearson et al., 2021
Wawa dam	Calawis	80	68	-	5.7	MWSS, 2016
	New Wawa	438	372.3	20 x 10^9	5.7	MWSS, 2016
Kaliwa dam	Kaliwa dam	-		12.2 x 10^9	-	MWSS, 2016
	Kaliwa	600	510	17.2 x 10^9	5.7	MWSS, 2016
Kanan dam	Kanan dam	-		14.4 x 10^9	-	MWSS, 2016
	Kanan	2,900	3,230	108.4 x 10^9	5.7	MWSS, 2016
Cavite	Cavite modular	54	45.9	-	22.8	MWSS, 2016; Pearson et al., 2021
Marikina	Marikina modular	27	23	-	22.8	MWSS, 2016; Pearson et al., 2021
Alternative Water Sources	Rainwater harvesting	255	-	24.8 x 10^3	1.4 x 10^3/unit/y	Oskam, 2013
	NRW recovery	-	-	25 x 10^6	-	Frauendorfer and Liemberger, 2010
	Seawater Desalination	-	-	25.7 x 10^3 / (m^3/d)	22.8	Pearson et al., 2021

To assess the environmental impact of the resulting networks, life cycle inventory was integrated into the P-graph model. The global warming potential (MtCO_2e) for the construction and operation of the WTP were obtained from the ecoinvent database of OpenLCA 1.10.3.

3.4 Integrating Analytic Hierarchy Process

To determine the prioritization of the main factors (i.e. GWP, CAPEX & OPEX, and Water Security) in relation to water supply planning in the concession area, a survey was conducted with respondents coming from key expert stakeholders (i.e., end-users and contractors) with adequate level of familiarity and experience about the topic. Pairwise comparison was done to determine the relative weight importance of each factor (Promentilla et al., 2018), which was then integrated into the P-graph results to calculate a sustainability score.

4. Results and Discussion

The case study illustrated how P-graph can generate optimal water supply networks through mathematical modeling. AHP complemented the results by integrating insights of experts on sustainability dimensions.

4.1 Analytic Hierarchy Process and sustainability scoring

A total of 10 respondents were consulted, with an average age of 28 years old and work experience of five years. Same number of respondents came from water supply network contractors and end-users (i.e. operators and analysts) to balance AHP results. Among the sustainability criteria, the respondents gave water security the most importance but differed on the succeeding priorities. According to one of the experts interviewed, "development can only be achieved if basic needs are met." End-users gave more importance on CAPEX and OPEX while contractors gave more importance on GWP contribution.

Table 3: Derived Relative Weights of Sustainability Criteria from AHP

Criteria	Overall (%)	End-Users (%)	Contractors (%)
Global Warming Potential	20	16	25
CAPEX & OPEX	21	32	13
Water Security	58	52	62
Consistency Ratio	1.0	0.1	5.4

4.2 P-graph simulation results

The simulation result amplifies the need of alternative water supplies because water security cannot be achieved (i.e., no solution) at crisis modes if the network only relied on the current MWSS infrastructure plan.

Table 4: Optimal and near-optimal P-graph simulation results

Structure	Global Warming Potential ($MtCO_2e$)	Combined CAPEX & OPEX (PHP)	Total Water Demand (m^3/d)	Sustainability Score (%)
1	671.3	128.0×10^9	8,480,000	89.2
2	671.3	128.0×10^9	8,480,000	89.2
3	668.5	127.8×10^9	8,480,000	89.2
4	667.9	127.7×10^9	8,480,000	89.2
5	667.9	127.7×10^9	8,480,000	89.2
6	664.0	127.7×10^9	8,480,000	89.1
7	660.5	127.4×10^9	8,480,000	89.0
8	657.2	127.5×10^9	8,480,000	88.9
9	653.8	127.1×10^9	8,480,000	88.9
10	649.3	127.0×10^9	8,480,000	88.8

Meanwhile, the sustainability scores of the top 10 optimal and sub-optimal networks did not veer away from each other, which means that any infrastructure combination shall not significantly impact the network's sustainability. The top networks were also the networks that can operate at crisis scenario.

Examining the infrastructure networks on Table 5 show remarkable insights. There were networks that did not require the construction of the controversial Kaliwa dam system while Kanan dam appeared for all the solutions. Compared to Kaliwa dam, which can provide up to 600,000 m^3/d only, Kanan dam has a maximum of 3,800,000 m^3/d and it tended to maximize its capacity.

Alternative water sources such as NRW recovery, saltwater desalination in rainwater harvesting were necessary in all the structures, especially with Maynilad. Compared to Manila Water, Maynilad had the higher water demand and shall experience the higher water deficit without the alternative water supply. The result highly suggests that the alternatives are necessary to be considered on top of the water roadmap to address water deficit, especially on crisis scenarios.

New Wawa and East Bay WTP, which are currently existing, were not part of P-graph solutions. These treatment plants have significantly lower capacity then the other treatment plants, making them the least priority. This suggests that once the entire water supply infrastructure program has been completed by 2037, these plants may be considered for decommissioning or retrofitted for different purpose, such as supplying other areas.

Table 5: Infrastructures used per optimal network structure

	Dams				Water Treatment Plants																			Alternatives		
Structure	Kaliwa dam	Kanan dam	Balara 1	Balara 2	Calawis	Cardona	Cavite	East Bay	La mesa	Kaliwa	La Mesa 1	La Mesa 2	Marikina	New Wawa	Kanan MWSI P1	Kanan MWCI P1	Kanan MWSI P2	Kanan MWCI P2	Putatan 1	Putatan 2	Putatan 3	Teresa	NRW Recovery	Desalination	Rain MWCI	Rain MWSI
1		X	X	X	X	X	X		X		X	X	X		X	X	X	X	X		X		X	X	X	X
2		X	X	X	X	X	X		X		X	X	X		X	X	X	X		X	X		X	X	X	X
3	X	X	X	X	X				X	X	X	X			X	X	X	X	X	X		X	X	X		X
4	X	X	X	X	X		X		X	X	X	X			X	X	X	X	X		X	X	X	X		X
5	X	X	X	X	X		X		X	X	X	X			X	X	X	X		X	X	X	X	X		X
6		X	X	X	X	X	X		X		X	X	X		X	X	X	X	X	X			X	X	X	X
7	X	X	X	X	X		X		X	X	X	X			X	X	X	X	X	X		X	X	X		X
8		X	X	X	X	X			X		X	X	X		X	X	X	X	X	X	X		X	X	X	X
9	X	X	X	X	X				X	X	X	X			X	X	X	X	X	X	X	X	X	X		X
10		X	X	X	X	X	X		X		X	X	X		X	X	X	X	X	X	X		X	X	X	X

4.3 Optimal water supply network

The optimal network is shown in Figure 2.

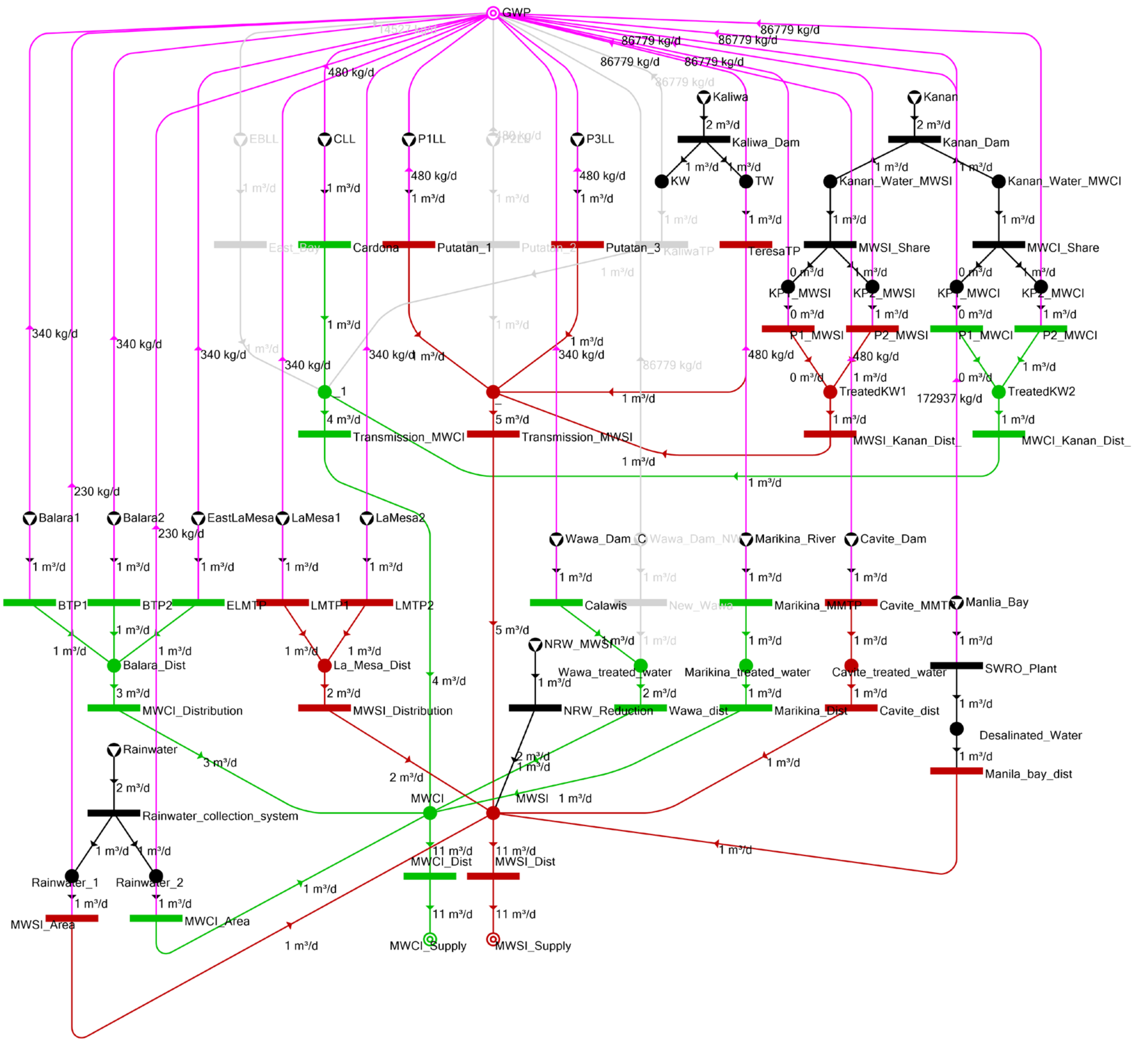

Figure 2: Optimal P-graph Network

The network did not use the Kaliwa dam system, East Bay, New Wawa, and Putatan 2 WTP. It utilized all the available water supply alternatives. Results are summarized on Table 6.

Table 6: Sustainability criteria results of the optimal energy network

Sustainability Criteria	Results
GWP ($MtCO_2e$)	671.3
CAPEX & OPEX (PHP)	128×10^6
Total Water Supply (m^3/d)	8,480,000 (15 % higher than normal demand)

5. Conclusions

The study used integrated P-graph and AHP in the design of sustainable water supply network in Metro Manila, Philippines. The sustainability score was defined through AHP with the objectives of having high water security, low GWP, and low CAPEX and OPEX. AHP showed that water security was the most prioritized criteria. The P-graph maximal structure was constructed using the MWSS water infrastructure plan. The simulations revealed that some options did not require the construction of the controversial Kaliwa dam. Alternative water supplies from rainwater harvesting, NRW recovery, and seawater desalination are necessary to reach the water deficit, especially for Maynilad. As the water supply infrastructure is completed in 2037, simulation showed that several low-capacity plants are no longer practical to operate and may be considered for decommissioning. The optimal water network supply used all the alternative water supplies but did not suggest the construction of Kaliwa dam, and operation of low-capacity plants. Overall, the integrated P-graph – AHP framework showed its utility in planning for sustainability to identify and implement long-term projects, notably in water supply networks.

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