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INTEGRATING LAND USE ANALYSIS WITH WATER DEMAND ESTIMATION: A CASE STUDY OF PUTRAJAYA, MALAYSIA

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Abstract

The challenges posed by population growth, urbanization, and changing land use patterns on sustainable water resource management are significant. This paper puts forth an integrated framework aimed at assessing future water demand in Putrajaya, Malaysia. The proposed framework combines population projections, estimations of water demand, and analyses of land use activities. Through an examination of demographic trends and land use patterns, the framework predicts population growth and identifies areas with high water demand. Daily water use patterns in homes and businesses (temporal analysis) inform the designing future water infrastructure, incorporating temporal aspects. Statistical and spatial analysis techniques are then utilized to merge these projections with water demand estimations to quantify water requirements in various zones and types of land use. This study has unveiled two daily peaks in water demand, which align with household schedules. Residential areas emerge as the primary consumers of water, displaying an evening peak distinct from the midday peak seen in businesses. The current water demand in Putrajaya is estimated at 94 million litres per day, with domestic usage surpassing non-domestic usage in a ratio of 3:2. Projections based on future land use plans foresee a 19% increase in demand, underscoring the urgency for proactive water management strategies. Spatial analysis has highlighted residential areas as the main users of water, with demand levels varying throughout the city. By comprehending these temporal and spatial patterns, water authorities can strategically target interventions, optimize infrastructure siting, and forecast future demand trends. These proactive measures are essential for securing a sustainable water future for Putrajaya.

Keywords: Sustainable Water Resource Management, Population Forecasts, Water Demand Estimation, Land Use Activities, Spatial Analysis

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INTRODUCTION

As a crucial natural resource, water plays a vital role in supporting life (Leitão et al., 2019) and facilitating various economic activities (Santos et al., 2021). The rapid development to meet human needs has led to a constrained and jeopardized supply of clean water (Rashid et al., 2021). Recent years have seen significant factors like climate change, population growth, urbanization, and industrial expansion impacting a rise in water consumption while diminishing available water reserves (Leitão et al., 2019; Pagsuyoin and Santos, 2021). Studies by Hasibuan et al. (2024) have highlighted swift urban development changes in major Southeast Asian cities characterized by population growth, increased building density, and clustering of economic activities. Forecasting water demand is crucial for effective water resource management (Stańczyk et al., 2022). Understanding the interplay between urban water demand, infrastructure, and population forecasts is essential in environmental planning. The accuracy of water demand forecasting depends on true population data, water consumption information, and understanding consumer types, land uses, and socio-economic factors, especially within communities (Azlan et al., 2022; Nigam and Ragi, 2016).

The escalating demand for potable water and the challenges related to water scarcity and diminishing water supply in Putrajaya, Malaysia, are urgent issues that need immediate attention. Changes in land use driven by population and economic growth have had an impact on Malaysia (Mohamad et al., 2023). With forecasts indicating 85% of the population shifting to urban areas and a projected population of 33.8 million by 2040 in Malaysia, an increase in built-up regions is expected (Samat et al., 2020). Despite abundant water resources, Putrajaya's urban transport system predominantly focuses on land-based modes, indirectly contributing to water scarcity through urban development and related activities (Jiang, 2023). Efforts to address water scarcity in Putrajaya include setting standards and exploring alternative water sources such as greywater reuse and wastewater treatment for reuse (Azhar, 2024). Maintaining the ecological balance of wetlands and lakes like Putrajaya Lake is emphasized through integrated water quality monitoring and catchment management practices (Najah et al., 2021). Pollution incidents, caused by substances like brominated flame retardants in water sources like Sungai Buah, have led to water shortages affecting water supply in areas like Putrajaya (Sha'arani et al., 2019). These challenges highlight the need for sustainable water management practices and effective water quality standards to ensure clean water availability amid the growing demands from Putrajaya's population and urban development.

Multiple studies have showcased the successful application of population forecasting, water demand estimation based on land use activities, and temporal and spatial analysis to improve water management in urban areas. For example, Baskoro et al. (2021) developed a system dynamics model for sustainable water supply strategies in Sentul City, focusing on predicting water supply and demand and analysing policies on wastewater management and rainwater harvesting. This model provided insights into effective water resource planning and allocation. Similarly, Praveena et al. (2019) conducted a study in Putrajaya, Malaysia, focusing on pharmaceutical residues in drinking water, highlighting the importance of analysing water quality parameters to address potential health risks. Additionally, Fazli et al. (2018) utilized spatial similarity-based modelling to predict water quality in Malaysian lakes, demonstrating the value of advanced modelling techniques for sustainable water quality management.

The recent Selangor water crisis, including Putrajaya, underscores the importance of water demand control as part of Economic Scarce Water control (Lim, 2019; Yusof, 2019). Given the diverse activities associated with land use, water supply management in Putrajaya heavily relies on estimating water requirements for all activities (McKinsey and Company, 2009). With a growing population necessitating more space for infrastructure, public facilities, and housing (JPBD, 2016), integrating these approaches enables city planners and water managers to forecast population growth accurately, estimate water demand effectively, and conduct comprehensive temporal and spatial analyses to optimize water allocation strategies, ensuring efficient water distribution and sustainable water management practices.

RESEARCH METHODOLOGY

Study Area

Putrajaya, the federal administrative capital of Malaysia, is characterized by its modern urban setting with a diverse population, varied land utilization, and water usage profiles. Investigating water demand in Putrajaya can yield valuable insights applicable to other urban areas in Malaysia and similar regions globally. Encompassing a land area of 49.3 km^2 divided into eleven precincts, which include residential zones, Putrajaya's structured development offers a controlled setting that helps mitigate potential factors that could influence water demand analysis. Elements such as urban planning regulations, infrastructure growth, and population dynamics can be more readily managed in a meticulously planned city like Putrajaya. Furthermore, Putrajaya is expected to possess abundant and detailed data on water consumption, population demographics, land usage, and infrastructure, which can greatly aid in conducting precise analyses and modelling of water demand trends.

Water consumption in Putrajaya is categorized into two main segments: domestic and non-domestic (Ryan, 2014). In the context of this study, "domestic water use" encompasses the consumption of water for household purposes, both indoors and outdoors, such as drinking, cooking, cleaning, bathing, laundry, and watering plants and gardens. On the other hand, "non-domestic consumption" pertains to water usage in commercial, industrial, and public settings like shops, offices, hospitals, and schools. Industrial water consumption is influenced by production processes and technological resources, typically quantified in litres per unit of raw material or product (Anang et al., 2019). The specific details related to the study area for both domestic and non-domestic sectors in Putrajaya are outlined in Table 1.

Table 1: Description of the study area

Precinct	Type of premises/buildings
Precinct 1	Government office (main), mall, complex, school, mosque, business centre, hotel, restaurant, cooling plant
Precinct 2	Government office, business centre, cooling plant
Precinct 3	Government office, business centre, mosque, , cooling plant
Precinct 4	Government office, business centre, restaurant
Precinct 5	Residential, government office, school, hall, cooling plant
Precinct 6	Residential, government office, sports complex
Precinct 7	Government office, business centre, hospital
Precinct 8	Residential, government office, school, business centre, wet market, restaurant, petrol station, library, hall, complex
Precinct 9	Residential, government office, school, business centre, restaurant, petrol station, hall/complex
Precinct 10	Residential, government office, hall, complex
Precinct 11	Residential, government office, school, restaurant, petrol station, clinic, hall/complex
Precinct 12	Residential, construction sites
Precinct 13	Corporate office, wetland
Precinct 14	Residential, government office, school, complex
Precinct 15	Residential, government office, school, business centre, restaurant, hall/complex
Precinct 16	Residential, government office, school, business centre, restaurant, petrol station, hall/complex, wet market, sports facility
Precinct 17	Residential, school
Precinct 18	Residential, government office, school, business centre, restaurant, petrol station, hall/complex, futsal complex
Precinct 19	Corporate office, water treatment plant
Precinct 20	Corporate office, place of worship, cemetery

Population Forecasting Methods

Designing a water supply network to fulfill water demand relies on projected population figures for a specific city or town for the design timeframe. If this figure is underestimated, the system may be inadequate, whereas overestimation can lead to unnecessary costs. Population dynamics in a city change over time due to various factors like births, deaths, migration, and annexation, necessitating the need for the system design to consider the projected population at the end of the design period (Anisha et al., 2016). Influential factors on population changes include increases from births, decreases from deaths, variations due to migration, and changes from annexation (Mekonnen, 2018). Various methods of population forecasting are utilized to perform comparative analyses to predict population trends in Putrajaya City.

1. Arithmetic Increase Method

The Arithmetic Increase Method is a straightforward way of predicting population trends, even though it tends to provide conservative estimates. This method assumes a consistent population growth rate from one decade to the next. The average population increase per decade is calculated by analysing census data from previous decades. This average increment is then projected forward by adding it to each successive decade's population projection. The formula to calculate the future population (Pn) after n decades is as follows:

$Pn=P+nI$ ………………………… (1)

where Pn is the future population at the end of *n* decades from present, P is the present population, and I is the average increment for a decade.

2. Geometric Increase Method

The Geometric Increase Method involves assuming a consistent percentage growth in the population from one decade to the next. By analysing population data from previous decades, the percentage increase in population is calculated and averaged. If IG represents the geometric mean percentage, the formula to calculate the population (Pn) after n decades from now is as follows:

$Pn=P(1+(IG/100))n$ ………………………… (2)

3. Exponential Growth Method

The Exponential Growth Method involves projecting population growth based on an exponential function, which signifies rapid growth over time. This method assumes that population growth continuously accelerates rather than remaining constant. It is particularly useful for modelling scenarios where growth rates increase over time, such as in developing cities or regions experiencing rapid urbanization. To forecast population growth, you need to know its growth rate by having at least two population estimates for different time points. Extending the model to cover longer time frames involves using linear regression, where the natural logarithm of the population size is regressed against time.

$P(t+n) = P(t) \times ern$ ………………………… (3)

where r is the constant annual growth rate,

$r = loge(P(t+n) / P(t)) / n$ ………………………… (4)

Water Demand Estimation

According to Malaysia's National Water Service Commissions (SPAN, 2018) uniform technical guidelines, the water supply requirements for development need to be specified in terms of total daily demands. These demands are typically determined by evaluating submitted layout plans, the proposed types of physical developments, and the unit rates of demand for various types of premises. In this study, the estimation of water demand was based on the guidelines provided by SPAN (2018).

Spatial Analysis Using Geographical Information System (GIS)

The spatial analysis employed in this study utilizes Geographical Information System (GIS) to merge spatial data (base map) with non-spatial data (land use data). Spatial overlays and interpolation techniques are utilized to analyse and estimate water demand across the study area. This analysis was carried out through two main approaches: area-based methods (zoning with land use data) or point-based methods (using demand data with land use activities). The resulting outputs include spatial demand maps that inform water management strategies such as infrastructure planning, leakage detection, and targeted water conservation efforts. Figure 1 illustrates the overall flowchart involved in this study.

Research Flowchart

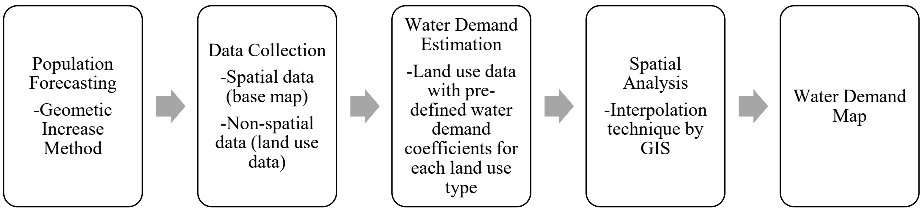

Figure 1: Overview of the flowchart of this study

ANALYSIS AND DISCUSSION

Population Growth Projection

The population of Putrajaya city was estimated using the latest census data provided by the Department of Statistics Malaysia (DOSM, 2024) in 2020 and projected for the next three decades up to the year 2050. Upon assessing all three methods, the Geometric Increase Method emerged as the most appropriate approach for this study. Moreover, the Geometric Increase Method works best in developing cities or towns where population increase is proportionate to the current population growth (Gawatre et al., 2016).

Table 2 and Figure 1 present the current and projected population growth figures for Putrajaya city, indicating a growth rate of 3.84 percent per year and an expected percentage change of 49 percent per decade. Consequently, the projected population by the conclusion of the study period in 2050 is 359,586.

Table 2: The present and projection population of Putrajaya city for the year 2010-2050

Year *projection	Arithmetical	Geometrical	Exponential
2010	73400	73400	73400
2020	109200	109200	109200
2030*	145000	162461	177837
2040*	180800	241700	289616
2050*	216600	359586	471654

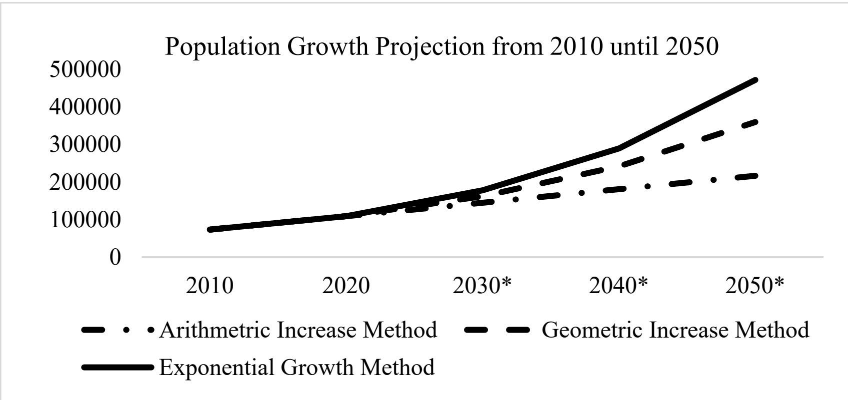

Figure 1: Population Growth Projection from 2010 until 2050 in Putrajaya

Temporal Analysis – Diurnal Pattern

Understanding peak water demand patterns throughout the day is crucial for optimizing water supply infrastructure design and operation. By aligning infrastructure capacity with peak demand times, utilities can ensure a reliable water supply without the need for excess construction or facing shortages during high-demand periods. Identifying the daily water consumption trends is vital for infrastructure optimization, efficient resource allocation, implementation of demand management strategies, system performance monitoring, and improving emergency response readiness in water utilities and management organizations.

Figure 2 depicts two distinct peaks in water demand, corresponding to morning and evening usage patterns. The morning peak occurs between 6:00 and 8:00 hours as individuals typically prepare themselves before heading to work. The evening peak, between 18:00 to 20:00 hours, is characterized by a significant increase in internal household water consumption. These findings are consistent with previous studies, as indicated by established patterns (Cole and Stewart, 2013). Around 54% of the average hourly household water demand during the morning peak (at 07:00 hours) is met through their respective water tank supply systems, while specifically 46% of the total demand during the evening peak hour (at 19:00 hours) is generally associated with end-user activities, such as toilet use, showers, kitchen tap usage, and dishwashing after individuals return home from work.

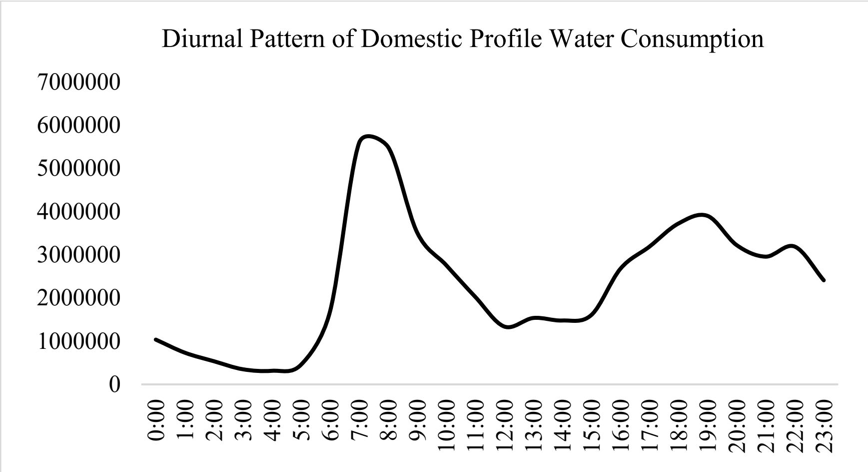

Figure 2: The diurnal pattern of water consumption for domestic profile

Non-domestic water consumption profiles tend to display a pattern where commercial and industrial usage peaks around midday and tapers off before the evening residential peak. Typically, residential water consumption constitutes the bulk of overall water usage for most utilities, showing up as the characteristic twin peaks in daily consumption. However, in specific supply areas or municipalities, the commercial sector might play a more significant role in altering this daily consumption pattern. Monitoring these diurnal consumption patterns enables water utilities to identify unusual usage patterns that could indicate leaks or inefficiencies in commercial properties. By swiftly identifying and addressing leaks, water utilities can minimize water loss, lower costs, and ensure the smooth functioning of the water distribution system.

In this study, Figure 3 illustrates the diurnal water consumption pattern for a non-domestic profile, wherein commercial customers, including governmental entities, accounted for 76.47% of the consumption, primarily during the 8:00-18:00 working hours. Given that Putrajaya comprises government facilities, a consistent pattern emerges during these working hours. Even in regions with higher proportions of commercial consumption, residential (domestic) water usage tends to have more daily fluctuations due to the relatively lesser variability in commercial consumption. Overall, various factors such as lifestyle choices, outdoor usage of water, appliance use, individual behaviors, and regulatory variations contribute to the increased water demand in residential areas compared to commercial sites (Cole & Stewart, 2013). Nevertheless, by pinpointing periods of high-water demand, utilities can prioritize infrastructure upgrades and expansion projects to meet the growing water needs of commercial establishments in a cost-effective manner.

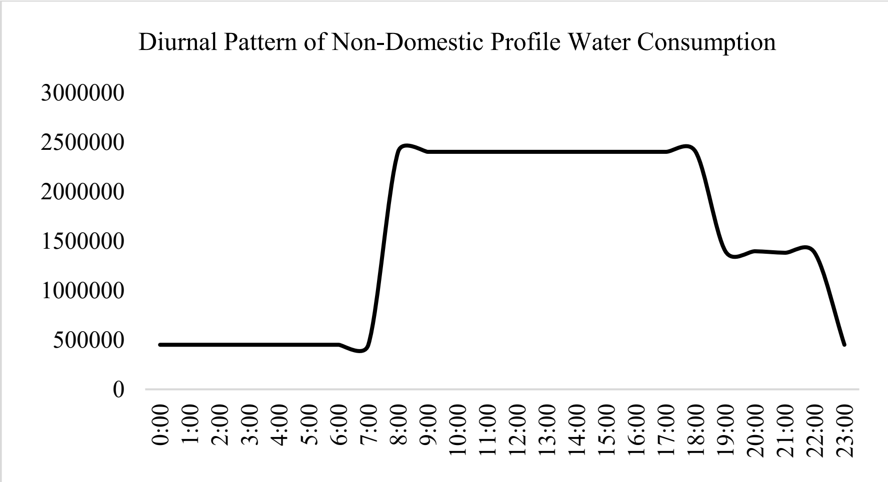

Figure 3: The diurnal pattern of water consumption for non-domestic profile

Water Demand Estimation based on Land Use Activities

According to the data presented in Table 3, the current total water demand in Putrajaya for 2023 is reported to be 94,233,765 litres per day. This total is distributed between the domestic sector, accounting for 58,102,500 litres per day, and the non-domestic sector, which comprises 36,131,265 litres per day. It is apparent from these figures that the demand is projected to rise continuously in parallel with the growing population. Additionally, taking into account the anticipated water demand for future city development, a further increase of 21,997,176 litres per day is predicted, representing an increase of 18.93%, leading to a total projected demand of 116,230,941 litres per day.

Table 3: The estimation of total daily average water demand for the present and future plan of land use category

Land use	Type	Total water demand (l/day)	Percentage (%)
Domestic			
Residential	Double storey terrace	7,003,500	**61.66**
	Triple storey terrace	357,000	
	Semi-detached	4,222,000	
	Apartment	43,656,000	
	Bungalow	652,000	
	Condominium	2,212,000	
Total		**58,102,500**	
Non-Domestic			
Government Use	Office	22,133,920	**38.34**
Commercial	Business centre	2,090,404	
	Restaurant	1,370,891	
	Hotel	100,500	
	Wet market	747,000	
	Petrol station	100,000	
Public Amenities	School	1,795,350	
	Hospital/Clinic	889,500	
	Mall/Hall/Complex	4,963,942	
	Mosque	1,750,000	
Service Industries	Cooling plant	189,757	
Total		**36,131,265**	
Differences between present and future land use water demand			
Current	**Total**	**94,233,765**	**81.07**
Future plan	**Total**	**21,997,176**	**18.93**
Total		**116,230,941**	**100.00**

The ratio of domestic to non-domestic areas is 3:2, corresponding to a ratio of 60:40 (DA: NDA = 60:40) according to the Malaysia Water Industry Guide (MWIG, 2018). Based on data presented in Table 3, the average daily water demand for domestic and non-domestic sectors was calculated to be 58,102,500 litres per day (61.66%) and 36,131,265 litres per day (38.34%) respectively, reflecting the 60:40 split. These estimates align closely with figures reported by the MWIG in 2018. A projection of future land use developments as outlined in the city's master plan combined with the current water demand indicates a significant surge in the need for clean water in the upcoming years.

Following the standards set by the National Water Service Commission (SPAN, 2018), the recommended range for clean water discharge from reservoirs is ideally between 0.0024 m3/sec and 0.0162 m3/sec. As Table 4 illustrates, four reservoirs in Putrajaya are currently utilizing more than 60% of their water supply capacity. Notably, reservoirs WR6 and WR3 share supply zone nodes, resulting in excessive capacity utilisation in WR6. Nonetheless, a comparison of the current clean water flow from reservoirs to the desired range reveals a shortfall.

Persistent over-extraction of water from reservoirs can trigger water shortages in urban areas, particularly during peak demand periods or dry spells. This predicament may necessitate water rationing, service disruptions, and interference with daily operations, affecting households, businesses, and public amenities. Consequently, it is imperative to conduct optimization analyses to tackle the challenges brought about by the limited availability of raw water in Putrajaya, especially in anticipation of future water demands.

Table 4: The reservoir capacity and its respective zone supply precincts

Reservoir	Zone supply precinct	Capacity (l/d)	Average water demand (l/d)	Percentage of capacity used (%)
WR1	7,8,9,10	30,283,294	23,619,452	77.99
WR2	2,3,4,18	52,995,765	11,145,851	21.03
WR3	1,12,14,15,16,17	45,424,941	30,430,314	66.99
WR4	5,6,20	37,854,118	11,155,484	29.47
WR5	11	15,141,647	11,882,227	78.47
WR6	15	3,785,412	6,000,438	158.51

***Some pipe nodes are sharing in the reservoir WR3 and WR6**

Spatial Analysis – Water Demand Distribution

Figure 4 illustrates the land use activities and current water demand distribution in Putrajaya city. The study's findings indicate that high water demand predominantly affects residents in residential areas. The spatial distribution of water demand varies based on the entry point of the distribution network. Utilizing the water demand map as a preliminary tool, priority areas can be identified for the implementation of protective measures. This paves the way for initiatives such as regional early warning systems, community involvement in conserving source water, and the establishment of communication programs to address water quality risks.

Understanding the spatial layout of water demand is crucial for optimizing the placement and capacity of infrastructure. This optimization involves strategically locating water treatment plants, reservoirs, pumping stations, and distribution networks in areas where they can efficiently cater to high-demand regions. Spatial analysis is instrumental in forecasting future water demand by considering factors like population growth, urban development, and land use alterations. Such forecasting aids in long-term planning for water resource management and infrastructure enhancement.

The land use map in Figure 4 indicates areas inclusive of precincts 8, 9, 10 (WR1), precincts 5, 6 (WR4), and precincts 11 and 13 (WR5) that exhibit higher vulnerability to contamination within the respective supplied zones. This data assists in identifying sectors and times of the year where monitoring efforts should be intensified. Notably, precinct 1 experiences a cluster of high water demand due to numerous government activities, while in precinct 13, elevated water demand is closely tied to wetland activities. By identifying these focal points, urban planners can strategically allocate resources and enhance infrastructure development to meet demand effectively. Further details on water demand classification are detailed in Table 5.

Table 5: The water demand classification

Classification	Total water demand (l/day)
Very low	0 – 20,000
Low	21,000 – 40,000
Moderate	41,000 – 60,000
High	61,000 – 80,000
Very high	81,000 – 1,000,000

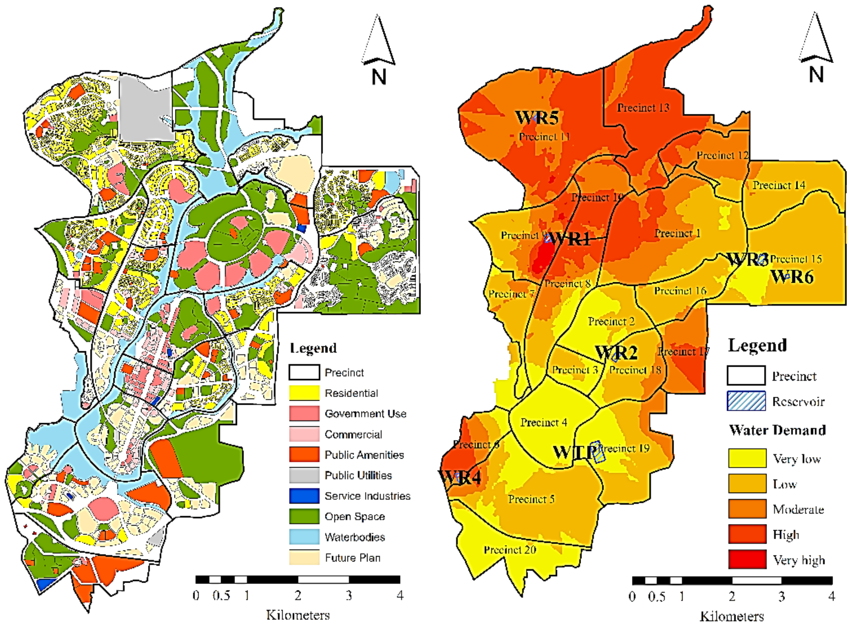

Figure 4: The land use map and water demand distribution in Putrajaya respectively

Water managers can utilize the outcomes of this study to prioritize their monitoring activities spatially and temporally, by considering various factors such as population vulnerability, infrastructure sensitivity, water quality indicators, and socio-economic deprivation. The water demand map facilitates the swift and clear ranking of areas based on the importance of protective measures. This aids local, state, and national authorities in deciding where to allocate resources for drinking water systems, such as treatment facilities and source water protection plans.

CONCLUSION

In conclusion, the study conducted in Putrajaya, Malaysia, integrating water demand patterns, unveiled distinct temporal and spatial trends. Daily water usage demonstrated a bimodal trend, with peaks corresponding to morning and evening household activities, emphasizing the dominance of residential consumption, particularly with a notable peak in the evening compared to the midday peak in non-residential sectors.

The current total water demand in Putrajaya stands at 94 million litres per day, with domestic use surpassing non-domestic consumption. Projections indicate an expected 19% rise in total demand due to future land use changes. Spatially, the analysis pinpointed residential areas as primary drivers of water demand, showcasing variations across the city.

These results underscore the critical importance of comprehensive water management strategies. Water authorities can strategically implement targeted protection measures in high-demand regions by leveraging insights into temporal and spatial water demand patterns. This understanding can guide the optimal placement of infrastructure to ensure efficient water supply and aid in developing long-term water resource management plans that consider projected population growth and changing land utilization patterns in Putrajaya.

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