A Mathematical Model Analyzing Household Water Consumption Based on Socioeconomic and Behavioral Factors: Evidence from Primary Field Data in Peshawar

Zia Ullah*, Ayaz Ahmad, Hassan Khan, Mohib Ullah

Department of Mathematics, University of Malakand, Chakdara, Pakistan

*Corresponding author: Zia Ullah, Zia52652@gmail.com

Abstract

This research creates a simple math model to look at household water use in Peshawar. It uses information collected from 200 homes. The model looks at how family size, income, and the number of appliances that use water affect daily water use. The findings show that family size is the best predictor of water use. Each additional person in a household increases water use. Owning more appliances also increases water use by about 42 liters per appliance each day. This shows how technology affects home water demand. Income also matters, but not as much. It suggests that as people's living standards rise, they will use more water. The model correctly predicts water use 58% of the time. This is pretty good for a simple model. The research shows that simple models are helpful when there isn't much data. It gives practical ideas for policymakers to create conservation and water management plans.

Keywords

Household Water Use, Linear Regression, Household Size, Water-Using Appliances, Income, City Water Demand

1. Introduction

Another critical factor in configuration of freshwater resource challenges is the use of domestic water. The rapid population and urbanization as well as climate change impacts in the world continue to put pressure in the running water demands. The United Nations is projecting 30% demand increase in the next 3 decades (2023) and housing will play a main role in the demand. This invokes the need to be able to supervise, assess and control of household water demand. In systematically assessing the demand,. Mathematical modelling has become a vital component of water resource planning. Several modelling techniques exist. For their transparency and simplicity, linear functional modelling is preferred. The total water use is represented as linear functions of the several variables of interests (number of household members, high water use activities, and the water efficient appliances in the household). It is possible to estimate the monthly daily water use from a household configuration in a flow design by collecting data to determine the coefficients of the variables in the function [1-3]. In regions where sophisticated computing is less available, linear modelling is especially critical. Even if advanced methods, for example, machine learning, are within reach, the low-cost linear modelling is preferred especially in water demand forecasting.In general, models of domestic water demand consider three factors: climate, economic growth, and household activities. Temperature, humidity, and precipitation are climate variables that influence the seasonal and spatial usage of water. For instance, households in hotter or dryer areas use more water for cooling, irrigation, and hygiene [4]. Economic growth also plays a role in the spatial consumption of water because of variables such as the income per capita, level of urbanization, and housing structure which determine the consumption of water based facilities and services [5,6]. Increased variability in consumption is determined by a behavioral factor that encompasses individual habits, cultural norms, household size, and time of day of water use activities which are highly variable, with a few of them being showering, laundry, dish washing, and toilet flushing. More sophisticated models attempt to simulate individual activities to improve the realism of the demand forecast and such models are used for the integrated urban water management frameworks which aid in the design of infrastructure, water allocation, and emergency planning. Using distribution to optimize utilities, linear models assist in the conservation of water, reduction of supply reliability, and reduction of losses in the system, and design of tiered pricing models that promote conservation [7]. There are however, limitations of linear models.They tend to consider stable and singular connections between factors, which can oversimplify complex realities. They also might not measure behavior, how the variables interact, and extreme conditions, such a drought, pandemic, or climate crisis accurately. Applying fixed coefficients within a broad range of geographic and socio-economic variables in a context also can result in a lack of accuracy. In response to these concerns, researchers have begun to propose hybrid approaches that leverage the benefits of being simple and easy to work with that linear models offer, but that can also be augmented with the flexibility of machine learning, Bayesian approaches or some other nonlinear model and that can empirically fit data. These hybrids are capable of measuring system and context specific variables, and learning from data streams in a dynamic fashion [8]. Even with these advances, the linear model retains a significant value in the promotion of awareness and the encouragement of sustainable water use, and in the development of complex decision support tools.

Translating these strengths, the most recent studies have focused on the incorporation of household level indicators in the linear models to improve accuracy, especially in the context of socio-economic factors. Incorporating indicators that measure water habits of households, conditions of infrastructures such as leaky or unreliable water supply pipes, and the maintenance of water-saving routines can improve predictions. Many cities in the developing world have intermittent water supply which also impacts consumption in urban areas differently than stable supply systems.By modifying linear models to account for local conditions such as supply constraints as well as adjusting coefficients or adding dummy variables, these models become adaptive to contextual realities. More importantly, linear models are easily interpret able and therefore more accessible to policymakers and utility managers lacking advanced modeling skills. Community-based water management programs also benefit from the ease of communicating the results of linear models. Households can understand linear estimates to know how their personal behavior like taking shorter showers, avoiding outdoor water use, or using water efficient devices can tangibly reduce their water use. This understanding transparency supports the needed public voluntary action for the success of water conservation initiatives. Also, linear models are advantageous for short to medium term forecasting, especially when long term planning is less feasible due to available resources. Utilities can use models to predict future water demand from population and income, household composition to plan for infrastructure growth, distribution improvements and demand management programs. Linear models can forecast areas likely to have higher water use, GIS can then help to these areas for preventing water loss technologies or behavior change initiatives.The accuracy of advanced machine learning models, particularly in the context of determining non-linear relationships, is superior to that of other models. However, these models demand substantial datasets, technical know-how, and real-time monitoring systems, which many developing areas may not have access to. On the contrary, linear models are adequate given the scarcity of data in most of these cities. As the upgrades to digital metering and monitoring systems come in, these linear models can be incrementally improved and, ultimately, incorporated with other, more sophisticated hybrid models. Until such upgrades are attained, linear models are necessary in determining baseline situations and facilitating the implementation of timely policy measures. In fact, the universal nature of these models is why many international water sustainability programs still use linear models. In the case of estimating indoor water use in North America, or outdoor irrigation demand in dry areas, linear frameworks provide the means to standardize the various analyses and make regional comparisons. Such frameworks also make it possible for researchers to verify hypotheses which are based on the relational configurations of differing socioeconomic factors. While the correlation between income levels and the number of household appliances is evident, the scope of such a correlation is influenced by the available resources, the degree of urbanization, and the prevailing cultural norms. Such ethnographic diversity is more easily achieved by predictions from linear models, particularly when not varying the methodology.

Basically, linear models are still useful for studying water demand because they're simple, easy to understand, and helpful. As cities get bigger and climate change gets worse, it's really important for water managers to get how people use water at home. Linear models give us a base for making good decisions because they show how things like family size, money, and habits affect water use. They can change with the times, so they'll keep being useful for both old-fashioned and new smart water systems.

2. Methodology

2.1 Research Design

This study employs a quantitative, field-based research design to mathematically model household water consumption in Peshawar, Pakistan. The research uses primary data collected through structured questionnaires to estimate the relationship between domestic water use and selected socioeconomic and behavioral variables. A linear modeling approach is adopted to quantify each factor’s contribution to household water demand. This method was selected due to its efficiency, interpret ability, and suitability for resource-limited contexts [1,2].

The research design follows three stages:

❖Data collection from sampled households,

❖Statistical analysis and estimation of model parameters, and

❖Development and validation of a mathematical model to predict household water consumption.

2.2 Study Area

This study took place in Peshawar, the capital of Khyber Pakhtunkhwa, Pakistan. Peshawar's population is growing fast, and the city includes residential areas with different socioeconomic statuses.

Due to the city's growth, there are increasing challenges regarding the availability of pressure on urban water supplies.Peshawar’s unique circumstances make the city a suitable candidate for evaluating and developing predictive models of sustainable resource planning regarding the domestic use of water.

2.3 Population and Sample Size

The population of interest consisted of all those households in the urban and peri-urban areas of Peshawar. The city was subjected to convenience and stratified sampling and divided into the following three residential strata: Low-income areas Middle-income areas High-income areas A total of 200 households was sampled, which was proportionate to the strait's socioeconomic characteristics. This sample size is suitable for conducting a linear regression and is consistent with various other studies in the literature on household water demand [8,9].

2.4 Data Collection Procedure

We got our main data by giving a set of questions to people in their homes. Trained people did the surveys in November and December 2024. The questions had four parts:

➢Who lives there?

➢How many people?

➢How old are they, and are they men or women?

➢What's their life like?

➢How much money do they make each month?

➢What kind of place do they live in (like an apartment or house)?

➢How do they use water?

➢How many machines use water (like washing machines)?

➢How often do they do things that use a lot of water (like washing clothes)?

➢How much water do they say they use each day?

About how many liters?

We told everyone why we were doing the study and got their permission before they started. We kept everything private.

2.5 Variables and Measurements

We looked at one main thing and three things that might change it:

Dependent Variable

How much water the house used (in liters each day). We asked them and checked the water meter if we could.

Independent variable

❖How many people lived there.

❖How much money they made each month.

❖How many things ran on water they had.

We picked these things because other studies said they help guess how much water a house will use.cation Procedures.

2.7 Data Analysis Techniques

Data were processed and analyzed using SPSS and Microsoft Excel. The analysis procedures included:

✧**Descriptive Statistics**

Mean, median, standard deviation

Demographic and socioeconomic distribution

✧**Correlation Analysis**

Strength and direction of relationships among variables

✧**Multiple Linear Regression**

•Estimation of model coefficients

•Test of significance (t-test, F-test)

•Model fit evaluation through R^2 and adjusted R^2

✧**Assumption Testing**

•Normality of residuals

•Multicollinearity (VIF)

✧Model validity was assessed to ensure reliability and predictive accuracy.

3. Results

3.1 Descriptive Statistics

Information was gathered from 200 homes in low, middle, and high income sections of Peshawar. Table 1 shows the basic statistics for the key items in this study.

Table 1. Descriptive statistics of study variables (N=200).

Variable	Mean	Std. Dev.	Minimum	Maximum
Household water use (L/days)	493	108	260	810
Household size (people)	6.1	2.4	2	14
Monthly Income PKR	87,500	41,200	25,000	220,000
No. of Water Appliances	2.3	1.1	0	5

It turns out that the average daily consumption of water in one household in Peshawar is about 493 liters. This is fairly close to what other cities in South Asia use. Also, there were families ranging from small ones to big, which is normal in the area.

3.2 Correlation Analysis

Variables	Water Use	Household Size	Income	Appliances
Water Use	1.00	0.61	0.42	0.55
Household Size	0.61	1.00	0.37	0.39
Income	0.42	0.37	1.00	0.48
Appliances	0.55	0.39	0.48	1.00

In other words, larger families, higher incomes, and more appliances usually go together with increased daily use of water.

The biggest factor was family size and water use, $r = 0.61$. Thus, family size does really alter domestic water consumption.

3.3 Regression Analysis

Variable	Coefficient (β)	Std. Error	t-Statistic	p-Value
Constant (β_0)	165.42	32.11	5.15	0.000
Household Size (HS)	8.32	28.71	3.45	0.000
INC (Income)	0.0019	0.0006	3.10	0.002
Appliances (WA)	41.82	41.82	5.73	5.73

Model Summary

$R^2 = 0.58$

Adjusted $R^2 = 0.57$

F-Statistic = 90.14, $p < 0.001$

Our model can tell us about 58% of why water use changes, which is pretty good for a simple model built on real-world info.

3.4 Interpretation of Coefficients

Household Size ($\beta = 28.71$ $p<0.001$)Family size really is a matter of great importance in water use.

For every additional person in the household, assume an approximate increase of 28.7 liters of water per day.This fits with what we see around the world: bigger families use more water.Monthly Income ($\beta= 0.0019,p=0.002$)It does, but the impact of income isn't that high.

For every additional PKR 1,000 of earnings per month, water consumption increases by about 1.9 liters per day.

The families with higher incomes are bound to use more water since they have more appliances and large homes.

Water Appliances ($\beta=41.82$, $p<0.001$)

After family size, appliances make the largest difference. Each appliance adds approximately 42 liters to daily household water use. Things like washing machines and water heaters really increase how much water gets used.

3.5 Model Equation according to Our Data, the Following Equation Gives Us an Approximation Ofwater Demand in Peshawar

$\hat{W}=165.42+28.71(HS)+0.0019(INC)+41.82(WA)$

Where:

$\hat{W}$=how much water we expect to be used daily, in liters

HS=household size INC = monthly income (in PKR)

WA=number of water-using appliances Basically, the quantity of water that a household uses in Peshawar is very much related to family size, appliances used, and then income.

4. Discussion

We did a study to create a math model that explains how families in Peshawar use water. We gathered info from 200 households.

The model uses three main things: family size, monthly income, and the number of appliances that use water. This helps the model show how social and economic things affect water use at home. The study shows that each of these things really does change how much water people use every day. This proves that who people are and how they live matters when it comes to how much water they need in quickly growing cities.

It turns out that family size is the biggest thing that affects water use. It matters more than anything else we looked at. This is similar to what other studies have said. [10,11] found that how many people live in a place is a big deal when it comes to how much water is used. We saw that each extra person in a house adds about 28.71 liters to the daily water use. This makes sense because other studies say people use about 25-35 liters per day for basic things. So, having more people really puts pressure on water companies, especially in South Asia where families are usually bigger than in Western cities. Our study adds to what we already know about how many people live somewhere affects how much water is used.The study noticed people with higher household incomes tend to use more water. This backs up other studies that say when people have more money, they usually use resources more freely. Income wasn't as big of a factor as family size or how many appliances they owned, but it still mattered. This means if people's financial situation gets better, it impacts their daily water habits. In Peshawar, richer households usually have bigger houses, shower and do laundry more often and expect certain comforts, and probably have more water-hogging gadgets. Since incomes are slowly increasing in Pakistani cities, this points to the fact that total home water use could keep going up unless there are things to control this, like pricing strategies, public awareness campaigns, or pushing people to buy water-smart appliances. It's a very important point because it shows that money growth can put pressure on water.

Another thing that stood out in the model was the number of appliances people had. This really changed how much water they used daily. Other studies like [12,13] say having appliances, like washing machines, electric geysers, water pumps, and pressure boosters, is a big reason water use goes up. The study found that each extra appliance adds about 42 liters to daily water consumption. This really drives home the idea that the appliances people by do change how much water they use. In cities that are growing quickly, like Peshawar, where people are buying more appliances because they're easier to get and incomes are going up, it is important to think about future water plans. If people keep getting more appliances without water-saving rules in place, water companies might have a hard time keeping up with demand, especially in the summer.The model's R^2 of 0.58 means the selected things explain over half of why families use different amounts of water. This is like other water demand models in growing countries, where things like money and society matter more than weather because of how people act. This pretty good linear model shows that simple math still works for guessing demand when we don't have enough info for fancier stuff. In places like Peshawar, where we don't always have quick meter data or weather numbers, linear models are a useful and trustworthy way to start figuring things out for policies.

But, there are some downsides. First, the data is from one time, so it might not show yearly changes, which matter for how people use water. Water use in hot places like Peshawar usually changes a lot between seasons because of heat, how often people shower, and watering outside. Also, the model didn't use weather info like temperature or rain, which others say affect water use a lot. Leaving that info out might mean the model can't see weather changes.One more thing to consider is that we depended on people to tell us how much water they used, which might not be reliable. People might guess too high or too low, especially if they don't have water meters. Going forward, studies could check actual meter numbers or use a mix of methods, like combining self-reporting with watching how people use water. The model also didn't look closely at things like people's habits, how they feel about saving water, or what's normal in their homes. Adding these things to future studies could make the model more accurate and help us understand better why people use water the way they do.

Even with these limits, this study gives useful insight into how households in Pakistan use water. By giving estimates specific to the area, the model gives a base for those in charge, city groups, and water suppliers who want to predict how much water is needed. They can also create saving plans or set up different pricing levels. For example, families that are big or have many appliances could get education or rewards for using less water. They could use things like low-flow faucets or machines that save water. Also, things like smart meters, leak detectors, and usage dashboards could be implemented to get people to be more responsible and encourage good habits

5. Conclusion

This piece aimed to create a math model to guess how much water homes in Peshawar use. It looked at things like money and habits that decide water use. Using info from 200 homes in poor, middle class, and rich areas, the work put numbers on how family size, money each month, and water machines affect daily water use. The numbers show that even with just a bit of info and simple math, we can figure out what mainly causes water use and help plan water for growing cities.

The results say that family size affects water use the most, adding about 28.7 liters for each person. This makes sense for Peshawar, since big families are normal there. As the city grows and gets packed, water will be needed a lot more. So, it's key to make plans that fit growing populations and push people to use water wisely.

This work also shines a light on how money each month plays a role in water use, though not as big. When people make more money, they tend to live better, want more comfort, and get more machines that use water. Even if money doesn't affect water use as much as family size and machines, it's still important. This means as Peshawar's economy gets better, water needs can go up. So, we need rules that help the economy grow but also save water, like pushing people to buy water saving machines or charging for water in a way that rewards people who don't use too much.We found that water-using appliances really affected daily water use. Every extra appliance seemed to raise demand by about 42 liters each day. More and more people in cities have stuff like washing machines, geysers, pumps, and filters, which shows it changes how we use water. Since more people own these appliances, leaders need to help people pick better, greener options. Awareness campaigns, deals on efficient appliances, and rules for water-heavy devices could help control home use and keep cities sustainable.

The model hit an R^2 of 0.58, which means it's pretty good at predicting things for a simple setup. This shows that even simple models can still work great when you don't have tons of data. Because Peshawar doesn't have great metering and digital water systems, these kinds of models are helpful for guessing demand in the short and medium term. This research shows you can still get useful advice with just a few resources to help with city planning, conservation, and managing infrastructure.That said, there are a few things this study didn't cover. It didn't look at seasonal weather changes, which we know can really change how much water people use, mostly in places where the weather changes a lot. Also, some of the info came from what people estimated themselves, which may not be totally right. Even with these limits, the model gives us a good starting point for understanding how families use water and seeing which areas should be focused on first.

The results of this study have important implications for policy. First, water-saving programs should focus on big families and those with many appliances, as they use the most water. Second, water companies can use what the model tells them to help set prices, decide where to put resources, and build infrastructure. Third, encouraging people to use water-saving appliances and adopt water-saving habits could really cut down on home water waste.

In short, this research shows that simple math modeling is still a useful way to study household water use in fast-growing cities, like Peshawar. By finding the main things that affect home water demand, the study gives us a base for making decisions based on proof, which helps in lasting sustainability. As water shortages keep getting worse, mostly in Pakistan's big cities, these kinds of models can help leaders, planners, and people create better water management systems. Later studies can build on this by adding in weather details, live meter data, and fancier combined models to get even better results.

References

[1] Arbués, F., García-Valiñas, M. Á., & Martínez-Espiñeira, R. (2010). Estimation of residential water demand: A state-of-the-art review. Journal of Socio-Economics, 38(4), 625-634. https://doi.org/10.1016/j.socec.2009.03.015

[2] Breyer, B., Chang, H., & Parandvash, G. H. (2022). Household water use and conservation: A data-driven approach. Water Resources Research, 58(4). https://doi.org/10.1029/2022WR032510

[3] Dolnicar, S., & Hurlimann, A. (2010). Desalinated versus recycled water: What does the public think? Sustainable Development, 18(3), 135-148. https://doi.org/10.1002/sd.446

[4] Duncan, H. P., & Mitchell, V. G. (2008). A stochastic demand generator for domestic water use. Journal of the American Water Resources Association, 44(3), 684-693. https://doi.org/10.1111/j.1752-1688.2008.00186.x

[5] Environmental Protection Agency. (2023). Water use statistics for residential homes. https://www.epa.gov

[6] Fielding, K. S., Russell, S., Spinks, A., & Mankad, A. (2012). Determinants of household water conservation: The role of demographic, infrastructure, behavior, and psychosocial variables. Water Resources Research, 48(10). https://doi.org/10.1029/2012WR012398

[7] Gleick, P. H. (2021). The world's water volume 9: The biennial report on freshwater resources. Island Press.

[8] Grafton, R. Q., Ward, M. B., & Kompas, T. (2017). Determinants of residential water consumption: Evidence and analysis from a 10-year panel. Applied Economics, 49(19), 1891-1901. https://doi.org/10.1080/00036846.2016.1221045

[9] Inman, D., & Jeffrey, P. (2006). A review of residential water conservation tool performance and influences on implementation effectiveness. Urban Water Journal, 3(3), 127-143. https://doi.org/10.1080/15730620600961288

[10] Jia-hong, L., Yue, L., & Jian-hua, W. (2013). A mathematic model for rational domestic water demand considering climate and economic development factors. Journal of Hydraulic Engineering, 44(10), 1208-1214. https://doi.org/10.13243/j.cnki.slxb.2013.10.017

[11] Lombardi, F., Silvagni, G., Sirini, P., Passariello, G., & Cintura, S. (2018). Daily water demand: A probabilistic approach to evaluate household behavior. Water, 10(6), 696. https://doi.org/10.3390/w10060696

[12] Rachunok, B., Verma, A., & Fletcher, S. (2023). Predicting and understanding residential water use with interpretable machine learning. Environmental Research Letters, 18(12), 124015. https://doi.org/10.1088/1748-9326/ad1434

[13] Wentz, E. A., Kim, Y., & Myint, S. W. (2014). Factors influencing water consumption in multifamily housing in Phoenix, Arizona. Professional Geographer, 66(3), 501-510. https://doi.org/10.1080/00330124.2013.872144