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Conceptual Framework and Computational Research of Hierarchical Residential Household Water Demand

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Abstract: Although the quantity of household water consumption does not account for a huge proportion of the total water consumption amidst socioeconomic development, there has been a steadily increasing trend due to population growth and improved urbanization standards. As such, mastering the mechanisms of household water demand, scientifically predicting trends of household water demand, and implementing reasonable control measures are key focuses of current urban water management. Based on the categorization and characteristic analysis of household water, this paper used Maslow's Hierarchy of Needs to establish a level and grade theory of household water demand, whereby household water is classified into three levels (rigid water demand, flexible water demand, and luxury water demand) and three grades (basic water demand, reasonable water demand, and representational water demand). An in-depth analysis was then carried out on the factors that influence the computation of household water demand, whereby equations for different household water categories were established, and computations for different levels of household water were proposed. Finally, observational experiments on household water consumption were designed, and observation and simulation computations were performed on three typical households in order to verify the scientific outcome and rationality of the computation of household water demand. The research findings contribute to the enhancement and development of prediction theories on water demand, and they are of high theoretical and realistic significance in terms of scientifically predicting future household water demand and fine-tuning the management of urban water resources.

Keywords: household water demand; Maslow's Hierarchy of Needs; urban water resources management; rigid water demand; flexible water demand; luxury water demand

1. Introduction

Over the past 20 years, water consumption within mainland China has shown a slowly increasing trend, whereby a stable growth rate has been maintained in terms of household water consumption

(Figure 1). While household water consumption does not account for a huge proportion of total water consumption, there was still a rather significant growth in consumption from 9.4% in 1997 to 13.6% in 2016 (Figure 2, ecological water consumption statistics began in 2003). Following intensive efforts to establish a water-conserving society in China since 2002, there has been a slowdown in the growth of the ratio of urban household water consumption to total water consumption [1]. However, household water consumption has still been showing a steadily increasing trend over a long period of time [2]. Meanwhile, statistics show that two-thirds of cities among the 668 cities in China experience different degrees of water scarcity [3]. With the double-barreled effect brought about by the new form of urbanization and climate change, problems related to water consumption in Chinese cities are expected to worsen in the future [4]. At present, a key urban water management task would be to accurately master the rigid household water demand of residents and to scientifically predict the change trends in future urban household water consumption in order to improve household water consumption efficiency while reasonably controlling the overly rapid increase in household water consumption [5].

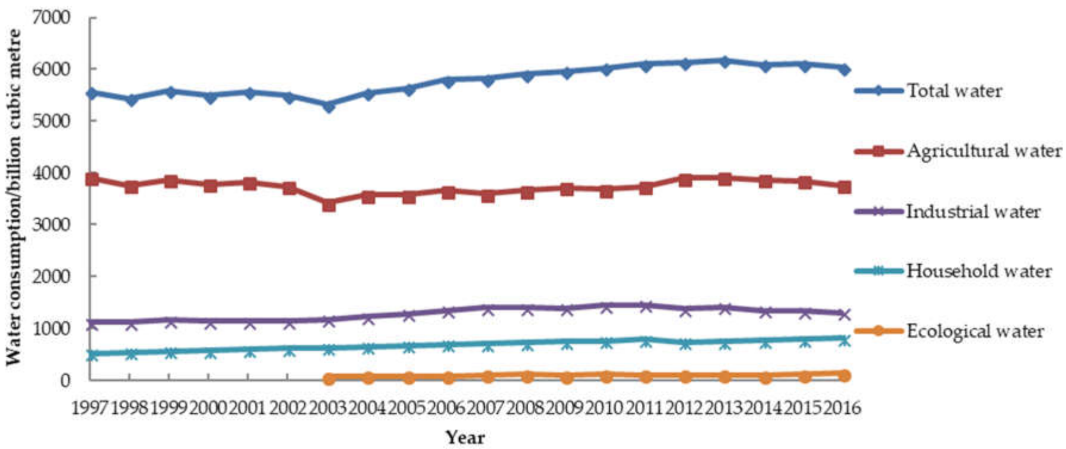

Figure 1. Evolution of water consumption in China based on different categories.

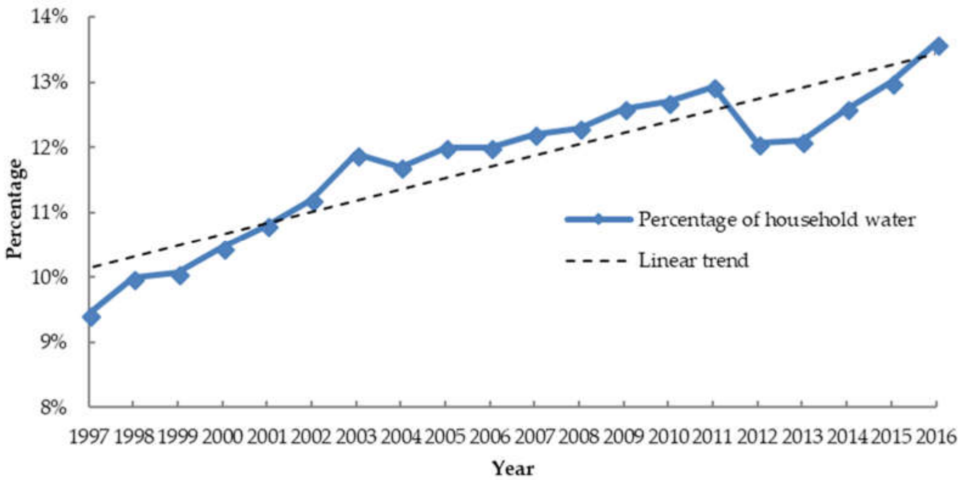

Figure 2. Percentage of household water consumption.

Rozos et al. used sociotechnical modeling to estimate the impact of various interventions on the evolution of the water demand of an urban area [6]. Bouziotas et al. have used a cellular automata approach to estimate the evolution of the water demand due to the expansion of an urban area (urbanization of the periurban area) [7]. In China, the quota method and the trend method are widely applied in predictions on water demand. The quota method needs to determine the water consumption quota based on the economic and social development. However, the water consumption per capita will not always grow along with the development. It will be essentially stable or will descend after a certain level of development. On the other hand, the change trends of the water consumption quota of various industries are different [8]. The trend method involves the use of the exponential growth curve to fit in historical water consumption data and then predict the future water consumption. However, the regularity of water demand is not obvious to all water users. There are many factors affecting the water demand of users, such as living standards, living habits, sanitation facilities, and the weather. Therefore, the trend of the water consumption quota is difficult to be accurately grasped [9].

It is worth noting that multiple predictions of water resources performed in China consistently found that the household water consumption quota will constantly show an increasing trend [10]. Due to the constant increase in population size, it has been predicted that future household water consumption will continue to be much higher than that of the base year [11]. With time, the predicted results of the water resource demand over different periods of time in China has gradually been proven; facts have shown that some of the predicted results were generally higher than the actual water consumption quantity for the corresponding periods [12]. On the one hand, higher forecasts might be due to certain cognitive errors, such as misconceptions that water consumption quantity will definitely increase with socioeconomic development, developing industries will definitely increase water consumption in great quantities, and urbanization will lead to huge increases in urban water consumption [13]. These misconceptions are actually due to the lack of understanding of the laws behind increased water demand arising from socioeconomic development, which stem from the failure to clearly ascertain the mechanisms and laws of water resource demand and the failure to explore the actual water demand from the perspective of water consumers [14,15]. On the other hand, relatively low water consumption values could be due to situations in which the actual water demand are not fulfilled and water users have been experiencing prolonged water scarcity [16].

Based on the analysis above, future water consumption predictions and management should reasonably fulfill the rigid demand of water users and control unreasonable water consumption demand based on the personal water consumption demand of water consumers to properly match water resources with the state of socioeconomic development. In addition, with the gradual increase in the proportion of household water consumption, the computation of residential household water demand will become the focus of water demand computations [17]. Influential factors include weather factors (temperature, precipitation, etc.), economic development standards (income, water consumption devices, etc.), household size and composition, water conservation awareness levels, etc. [18,19].

1. The influence of weather factors on household water demand. Thomas found that a reasonable household water quantity per person per day is approximately 100 L/d. In areas with different weather conditions, the quantity of residential water demand for bathing and laundry purposes would differ among residents due to different temperatures and precipitation levels [20]. As such, the reasonable quota for residential water demand also fluctuates. A study by Griffin et al. showed that temperature and precipitation levels have the greatest influences on residential household water demand, and higher temperatures would cause higher evaporation levels, which will result in increased water demand in terms of home gardens, sprinklers, home swimming pools, and drinking water. Meanwhile, precipitation levels mainly affected outdoor household water consumption in terms of home gardens, swimming pools, and washing cars. The quantitative analysis carried out by Balling et al. in Arizona, U.S.A., showed that a 10% reduction in annual rainfall levels could result in a 3.9% increase in per capita household water consumption [21]. On another note, a 1 °C increase in annual temperature levels could result in a 6.6% increase in per capita household water consumption. Using Xi'an, China as an example, the study carried out by Zhang et al. on per capita household water consumption predicted that with every 1.0 °C increase in annual temperature levels, the per capita household water consumption quantity

would increase by 1095 m^3 (3 L/d per capita). The study results above show that weather changes are a key reference point in terms of urban household water management.

2. The influence of economic development on household water demand. The study by Friedman on the residential household water consumption quantity and composition (toilet flushing, bathing, laundry, cooking) across the world found that the current household per capita water consumption quantity varies from 5.4–575 L/d, and the composition of water consumption is 45% for toilet flushing, 30% for bathing, 20% for laundry, and 5% for cooking [22]. Residential income levels are the key influencing factor that brings about the huge differences in residential household water consumption quantities. The semiquantitative analysis carried out by Newton et al. on the determining factors of urban water resource consumption (water resources, energy resources, residential) in Brisbane, Australia, found that the primary determining factor of water consumption quantity is income levels [23]. In the analysis of the residential household water consumption process and the computation of water consumption, Howe and Saleth et al. divided their research samples into groups based on their income levels, whereby different prediction methods and models were applied for groups with different income levels [24,25]. Shen et al. found that the largest influential factors on household water demand are increases in the population (to which water is supplied) and the average worker's salaries, which have a key influence in increased water demand, while prices did not have a significant effect on water demand [26]. Meanwhile, by consolidating the per capita household water consumption quantities and the gross domestic product (GDP) from different periods and areas both locally and abroad, a study by Zuo established a universally significant interval-type S-model for predicting the per capita water consumption quantity [27]. The study found that per capita household water consumption quantities increase with GDP growth initially and arrive close to a stable interval upon reaching a certain degree of growth. Yuan found that as household income increased, the per capita water consumption increased. As economic development standards increase, the production of household water consumption devices and the water prices increase. As residential household income levels increase, the number of household water consumption devices used increases, and the function of water prices in reducing water consumption becomes weaker. Hence, these factors would ultimately result in household water consumption being relatively high.
3. The influence of household size and composition on household water demand. The size and age composition of households as well as water consumption behavior also have a very large influence on the water consumption quantity [28]. Arbués found that population size had a scale effect on water consumption quantity, whereby an increase in household size would lead to lower per capita water consumption quantities [29]. Over the process of studying urban Swedish residential demand, Hoglund found that when the average household size increased from two to three persons, the per capita water consumption quantities within the neighborhood would fall by 27–35% [30]. In their studies of urban French household water consumption demand, Nauges et al. found that there was a negative relationship between the proportion of the elderly aged 60 and above and the neighborhood water consumption, primarily due to the water consumption habits and demand of the elderly [31]. Taking Nantong City, China, as an example, a study by Hu found that household water users aged 14–50 had the highest influence on water consumption demand, followed by the elderly aged 60 and above, with children aged 13 and below having the least influence.
4. The influence of water conservation awareness on household water demand. Water conservation awareness is not only related to education levels and the water consumption habits of household members but is also related to water conservation publicity efforts and the management standards of the local government [32]. In certain areas, people are used to bathing and doing laundry more often, while people in certain areas have stronger levels of water conservation awareness due to water scarcity in their areas [33]. By conducting observations and a behavioral analysis on

132 households in the Gold Coast, Australia, Rachelle et al. studied the effect that the presence or lack of water conservation awareness ultimately had on water consumption quantities [34]. In a study by Ma et al., which conducted an empirical analysis on the water conservation behavior among Beijing residents in China as an influencing factor, it was found that the existing policies on pricing levels in Beijing significantly motivated a number of residents to practice household water conservation behavior (such as purchasing water conservation devices and modifying water consumption devices for water conservation purposes) [35]. However, the said policies did not have a significant effect on cultivating household water conservation habits.

American psychologist Abraham Maslow established the well-known theory on Maslow's Hierarchy of Needs based on human demand, which shows that the constant fulfillment of demand enables humans to attain a state of self-development while promoting progress in society [36]. The demand are classified into five hierarchical categories, which are basic demand, safety demand, social demand, esteem demand and self-actualization demand, which progress from lower level demand to higher level demand. Once satisfying lower level demand, the demand are still present but are no longer the primary motivating factors. In turn, the next higher level need becomes the driving motivation for human behavior. Over this process, an individual's motivation is fully mobilized and they will constantly embark on objective-oriented practical activities and efforts in order to fulfill the said need. Maslow's Hierarchy of Needs theory reflects, to a certain extent, the common laws among human behavior and psychological activities. By identifying root issues through exploring human motivations and studying behavior based on their demand, it has been found that human demand constantly progress from lower level demand to higher level demand [37]. This trend is generally in line with the developmental laws concerning demand [38].

Analyzing and predicting the mechanisms of water demand are fundamental elements and core aspects of water resource planning, allocation, and management, as well as a key focus and difficulty of social water cycle research. This paper applied Maslow's Hierarchy of Needs theory in the computation of household water demand, establishing corresponding hierarchical theories on household water demand while conducting computational research on residential household water demand from the perspective of the actual water demand of humans. The final computation of the household water quota fulfills the rigid demand of residents for water resources without the wastage of water resources. Through this paper, we hope to enhance and develop prediction theories on water demand and present results of high theoretical and realistic significance in terms of predicting future household water consumption demand and fine-tuning the management of urban water resources.

2. Method

2.1. Categories of Household Water Demand

Based on research, it was found that the primary categories of water needed by residential households are water for drinking, cooking, washing, bathing, laundry, toilet flushing, home cleaning, home maintenance, and sports and recreation (the water demand categories might not be applicable to every household). The characteristics of the different water demand categories are mainly independent, where each water category exists on a parallel basis and generally does not overlap with other categories.

Water for drinking refers to water directly consumed by residents on a daily basis, including directly consumed municipal tap water, bottled water, and boiled water. This category does not include other products primarily made up of water, such as bottled water and drinks. Water for cooking refers to water used during cooking processes, such as washing vegetables, cooking, frying dishes, cooking soup, and washing pots and plates. Water for washing refers to water used for daily activities such as washing hands, washing faces, brushing teeth, washing feet, washing fruits, washing milk bottles and toys, and so on. Water for toilet flushing refers to water used for toilet flushing, while water for bathing refers to water used for bathing (showering, bathing, etc.). Water for home cleaning refers to water used for mopping, wiping, cleaning cooker hoods, and washing cars, while water for home maintenance refers to water used for humidification, watering plants, and rearing fish. Water for sports and entertainment refers to water-based toys and indoor swimming pools, while other water demand refers to water used for purposes other than those covered in the categories stated above.

The categories above generally cover the primary categories of water needed by households in their daily activities. In reality, not all categories may apply to all households, and different households may need different water categories. On another note, urban and agricultural households might have rather different demand in terms of water categories. Generally, agricultural households need fewer water categories compared to urban households, and impoverished agricultural households also need fewer water categories compared to wealthier households.

2.2. Characteristics of Household Water Demand

Unlike water used for production and ecological purposes such as agricultural and industrial water, household water is an indispensable element for human survival and progress that is closely intertwined with the daily activities of individuals. Household water is a basic need that arises from daily human activities that fulfill certain demand related to survival, leisure, comfort, hygiene, convenience, and aesthetics. The aforementioned categories of household water could be classified into three major levels, namely: (1) Drinking water demand for survival purposes; (2) water for hygiene-related purposes for the maintenance of health (e.g., bathing, laundry, toilet flushing, etc.); and (3) water for leisure and recreational purposes (e.g., watering plants, etc.). These hierarchical demand-related characteristics drive the formation of the household water cycle system and the constant changes in the hierarchical levels. These demand-related characteristics also activate the driving mechanisms of the household water cycle, which include consumer sociology, consumer behavior, and consumer economics. Based on Maslow's Hierarchy of Needs, the hierarchical structure of household water is shown in Figure 3. In this pyramid, water used for drinking, cooking, personal hygiene, laundry, and cleaning are ranked from lower to higher levels. Generally, upon fulfilling the demand in the lower levels, users will progress to higher levels as the economy develops and water facilities improve, at which point the pursuit of next level demand becomes the driving factor for user behavior. While none of the demand are eliminated over the course of progressing to the next level, the degree of the driving factors for the behaviors reduces. The elements of short-term survival, medium-term lifestyle maintenance, and long-term sustained progress among humans are reflected in the different levels of household water categories and quantities.

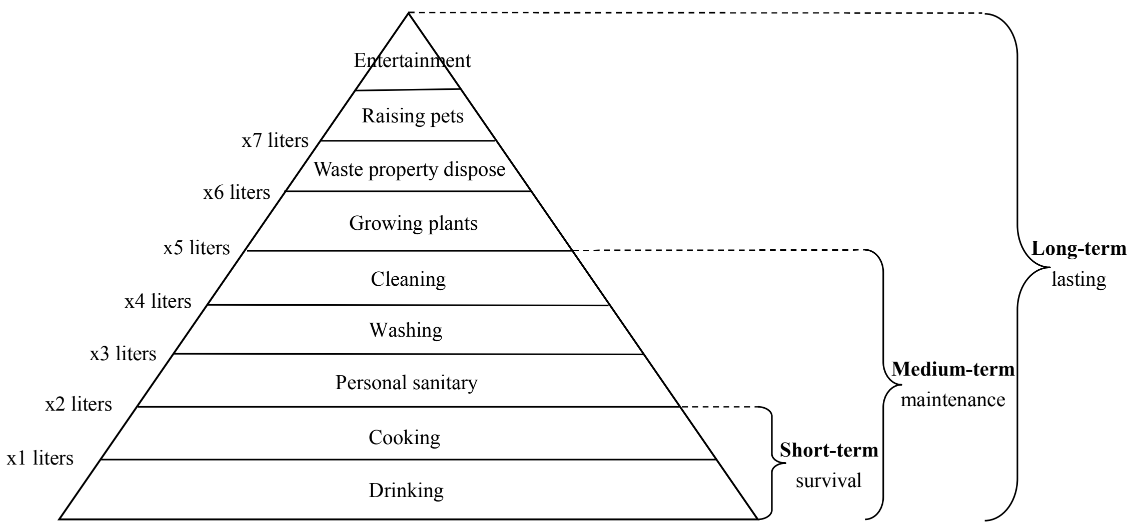

Figure 3. The hierarchical system of household water demand.

2.3. Theoretical Construction of the Level and Grade System of Household Water Demand

According to the analysis above, residents have hierarchical-based household water demand due to socioeconomic development according to the psychological and activity laws related to human demand. Based on this, the paper preliminarily proposed a theory of three levels and three grades for household water demand (Figure 4):

1. Rigid water demand: As the lowest level need for residential water resources, this category of demand is required for survival and primarily fulfills basic water demand and safety demand for the sustenance of life. The key purpose of this level is to address the physiological demand of humans for water and to eliminate threats to survival posed by water scarcity. The basic water demand of residents could be viewed as a basic human right that should be protected by the government under the scope of human rights, despite the market economy. The demand on this level should be fulfilled unconditionally, should not be influenced by market forces, and ought to be prioritized in terms of water resource allocation. Different residents have different rigid water demand in terms of categories and quantities. For certain groups (area-based groups), the categories and quantities of the rigid demand of urban and agricultural residents are different, whereby the different economic development standards of urban and agricultural areas would translate to different categories and quantities of rigid water demand.
2. Flexible water demand: To ensure an excellent quality of life in residents, relatively adequate water resources are provided within acceptable economic limits. This level of water demand usually increases in a gradual manner as living conditions improve. However, due to the regulation of water conservation measures and economic levers, water demand might fall after an initial increase before ultimately showing a stabilizing trend. With excellent resources and mature engineering conditions, the water resource allocation for this level of water demand should be prioritized, the failure of which may result in a decline in the living standards of residents. On the condition that it does not affect the quality of living in residents, the water consumption efficiency should be increased as much as possible through water management methods that dynamically regulate flexible water demand in order to maintain residential water demand within reasonable limits.
3. Luxury water demand: At this stage, the water consumption efficiency could still be improved, and the excess portion arising from the difference in efficiency rates from developed countries with higher water consumption efficiency rates is known as luxury water demand. This type of need should be continually reduced through different control measures in order to gradually slash the quantity, and the quantity of water demand that cannot be slashed could then be fulfilled in an appropriate manner. Meanwhile, as residents pursue higher standards of living, the water consumption of high-grade activities such as sports and recreation or washing cars that are carried out during normal years should be reduced during dry years since these are regarded as luxury demand. In future stages, when residents are wealthier in terms of living standards and a certain degree of water conservation standards is attained, the entire society will not experience water resource wastage and the water consumption efficiency will be extremely high. At this point, the water demand of residents could virtually be fulfilled unconditionally, and luxury water demand could be largely converted into reasonable demand. While luxury water demand are relatively low, various measures should be adopted to reduce the quantity in order to realize the sustainable development of the water resource system, with the ultimate goal of eliminating luxury water demand.

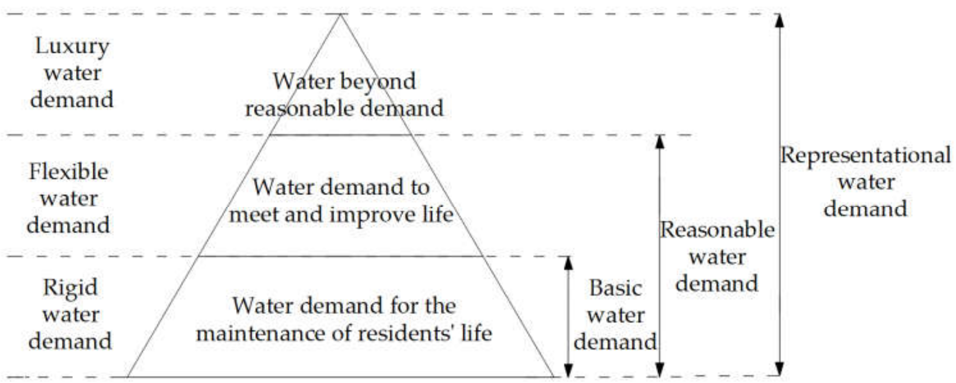

Figure 4. The level and grade framework of household water demand.

2.4. The Construction of Equations for Different Categories of Household Water Demand

In consideration of the occurrence characteristics and the demand characteristics of behavior for different categories of water demand, we needed to separately construct different computational methods for the water quantities needed for different categories of water demand.

Based on the findings of 536 survey results from Beijing respondents and 482 survey results from Tianjin respondents on household water consumption, combined with the observational and experimental data of typical households, equations for different household water demand categories were preliminarily constructed according to categories comprising water used for drinking, cooking, bathing, laundry, toilet flushing, washing, and home cleaning.

2.4.1. Computation of Drinking Water Demand

The study found that temperatures had a rather large influence on drinking water demand. Using 20 °C as a benchmark, the quantity of daily drinking water needed by household members was computed as follows:

$$Q_{i,\ drink} = \begin{cases} U_{a,\ drink} \cdot N_a + U_{c,\ drink} \cdot N_c,\ if\ T_i < 20\ ^\circ\mathrm{C} \\ (U_{a,\ drink} \cdot N_a + U_{c,\ drink} \cdot N_c) \cdot 0.05 T_i\ ,if\ T_i \geq 20\ ^\circ\mathrm{C} \end{cases} \quad (1)$$

In the equation, $Q_{i,\ drink}$ represents the quantity of drinking water demand of household members on the *i*th day of the year (unit: L); $U_{a,\ drink}$ represents the quota of basic daily drinking water demand for adults, which is generally 1.5 L/d; $U_{c,\ drink}$ represents the quota of basic daily drinking water demand for pupils, which is generally 1.0 L/d; N_a represents the number of adults aged 18 and above in the household; N_c represents the number of pupils aged 18 and below in the household; and T_i represents the simulated average temperature of the day.

2.4.2. Computation of Cooking Water Demand

For household members, the frequency of eating at home on working and nonworking days is different, and there is a rather irregular pattern of eating at home. In view of this, the study used a probability function while performing the computations. The daily cooking water demand of household members was computed as follows:

$$Q_{i,\ eat} = (1+\varphi) \cdot U_{eat} \cdot \left(N_{a1} \cdot |P(a1) - R(a1)| + N_{a2} \cdot |P(a2) - R(a2)| + N_c \cdot |P(c) - R(c)|\right) \quad (2)$$

In the equation, $Q_{i,eat}$ represents the quantity of cooking water demand of household members on the *i*th day of the year (unit: L); U_{eat} represents the average daily quota of cooking water needed per person under normal circumstances, which can be determined through observations or surveys; N_{a1}, N_{a2}, and N_c respectively represent the number of household members aged 60 and above (elderly), between 18–60 (youth and adults), and 18 and below (pupil); P represents the probability of household members eating home-cooked food in the year (classical statistical frequency is generally used to replace probability), whereby $P(a1)$, $P(a2)$, and $P(c)$ respectively represent the probability of the elderly, youth and adults, and pupils eating home-cooked food; $R(x)$ represents the generation of random numbers uniformly distributed between 0–1; $| \ |$ is to derive the absolute value; and φ represents the expansion correction coefficient of the quota of water demand. Generally, the intensity of cooking water demand on non-working days would be higher, which resulted in the correction used for the said parameter in the computation to predict the quantity of water demand for household cooking with values generally within the range of 0–0.6; on working days, $\varphi = 0$.

2.4.3. Computation of Bathing Water Demand

Studies have found that temperatures had a rather large influence on bathing water demand. The daily bathing water demand of household members was computed as follows:

1. The survey found that should the average temperature of the day be $T \geq 25$ °C, the frequency of bathing for all family members would change to once a day, whereby:

$$Q_{i,bath} = N \cdot [B_0 + \Delta B \cdot f(x)] \tag{3}$$

In the equation, $Q_{i,bath}$ represents the quantity of bathing water demand of household members on the ith day of the year (unit: L), N represents the number of household members, B_0 represents the basic quantity of water demand for one bath (unit: L), ΔB represents the additional bathing water demand with the development of economic standards, and $f(x)$ represents the function of the per capita household water index with the changes in per capita GDP. The computation method for $f(x)$ is:

$$f(x) = \frac{1}{2} + \frac{1}{\pi} \tan^{-1} \left(\frac{x-3}{\alpha}\right) \tag{4}$$

In the equation, x represents the per capita GDP and α represents the elasticity coefficient, which characterizes the sensitivity of the per capita household water demand with changes in GDP.

2. Should the average temperature of the day be $T < 25$ °C, the frequency of bathing for all family members would change to once in n days, whereby:

$$Q_{i,bath} = N \cdot \left|\frac{1}{n} - R(b)\right| \cdot [B_0 + \Delta B \cdot f(x)] \tag{5}$$

In the equation, $\frac{1}{n}$ represents the frequency of household members bathing on the ith day and $R(b)$ represents the generation of random numbers uniformly distributed (between 0–1), while the other symbols represent the same elements as in the equations above.

2.4.4. Computation of Laundry Water Demand

Since people generally wash their clothes after bathing, the frequency of doing laundry and bathing are generally about the same, and the computation for laundry water demand is similar to that of bathing water demand.

1. When the average daily temperature is $T \geq 25$ °C, the frequency of doing laundry would be once a day, whereby:

$$Q_{i,clothes} = N \cdot [L_0 + \Delta L \cdot f(x)] \tag{6}$$

In the equation, $Q_{i,clothes}$ represents the quantity of laundry water demand of household members on the ith day of the year (unit: L); N represents the number of times clothes are washed per day;

L_0 represents the quantity of water needed for one cycle of laundry (unit: L); ΔL represents the additional water needed for laundry as economic standards develop; and $f(x)$ represents the function of the per capita household water index with changes in per capita GDP. The computation method is the same as above.

2. Should the average temperature of the day be $T < 25$ °C, the frequency of doing laundry for all family members would change to once in n days, whereby:

$$Q_{i,clothes} = N \cdot \left| \frac{1}{n} - R\ (w) \right| \cdot [L_0 + \Delta L \cdot f(x)] \tag{7}$$

In the equation, $R(w)$ represents the generation of random numbers uniformly distributed (between 0–1), while the other symbols represent the same elements as in the equations above.

2.4.5. Computation of Toilet Flushing Water Demand

The quantity of water needed for toilet flushing is mainly determined by the type of toilet bowl used in the household, the quota of water needed for toilet flushing, and the frequency and number of times that household members use the toilet. The frequency of toilet usage in household members is mainly determined by the amount of time that household members spend at home.

$$Q_{i,toilet} = U_{toilet} \cdot S \cdot \left(N_{a1} \cdot \frac{T_1}{24} + N_{a2} \cdot \frac{T_2}{24} + N_c \cdot \frac{T_3}{24}\right) \tag{8}$$

In the equation, $Q_{i,toilet}$ represents the quantity of water needed for toilet flushing by household members on the ith day of the year (unit: L); U_{toilet} represents the quantity of water needed in households for a single flush (unit: L); S represents the number of times a person normally uses the toilet per day, which is generally 6–9 times a day based on medical data [39]; N_{a1}, N_{a2}, and N_c respectively represent the number of middle-aged and elderly, youth and adults, and children in the household; and T_1, T_2, and T_3 respectively represent the duration of time that household members spend at home according to different age groups (unit: hour).

2.4.6. Computation of Washing Water Demand

The quantity of water needed for washing is mainly determined by the frequency and number of times that household members perform washing activities. In addition to washing activities in the morning and at night, the frequency of washing by household members is directly correlated to the duration of time that household members spend at home.

$$Q_{i,wash} = U_{wash} \cdot S \cdot \left(N_{a1} \cdot \frac{T_1}{24} + N_{a2} \cdot \frac{T_2}{24} + N_c \cdot \frac{T_3}{24}\right) \tag{9}$$

In the equation, $Q_{i,wash}$ represents the quantity of water needed for washing by household members on the ith day of the year (unit: L); U_{wash} represents the quantity of water needed for one cycle of washing (unit: L); S represents the number of times a person normally performs washing activities in a day, which is based on observations and experiments or surveys, while the other symbols represent the same elements as in the equations above.

2.4.7. Computation of Home Cleaning Water Demand

The home cleaning demand of household members was computed as follows:

$$Q_{i,env} = U_{env} \cdot A \cdot |P(e) - R\ (e)| \tag{10}$$

In the equation, $Q_{i,env}$ represents the quantity of water needed for home cleaning on the ith day of the year (unit: L); U_{env} represents the quota of water needed to clean every square meter under normal conditions (unit: L), A represents the residential area of the household (unit: m^2); $P(e)$ represents the probability of home cleaning behavior taking place, which is generally represented by the frequency of home cleaning per week; and $R(e)$ represents the generation of random numbers uniformly distributed between 0–1. Please refer to the text above for further details.

Water needed for home maintenance and sports and recreation are not as common in most households, and observations, experiments, or surveys could be applied for these activities, whereby empirical parameters are used to determine the quantity of water used.

2.5. The Construction of Equations for Different Levels of Household Water demand

Based on the computational equations of different household water demand categories shown above, equations for household water demand on different levels were constructed.

In principle, the different categories of water demand above form the general representational household water demand (Figure 5). As such, the equation for representational household water demand could be constructed as such:

$$W_k = (1+\beta_k)\sum_{j=1}^{n}\alpha_{k,j}\cdot Q_j \quad (11)$$

In this equation, k represents the different levels of water demand (rigid water demand, flexible water demand, and luxury water demand, k = 1, 2, 3), j represents the different categories of household water demand (j = 1, 2, 3, $\cdots$, n), $\alpha_{k,j}$ represents the empirical coefficient of household water demand in different categories and on different levels, Q_j represents the quantities needed for different household water demand categories, and β_k represents the correction coefficient for household water demand on different levels (in consideration of repeated consumption, reuse and seepage losses, etc.).

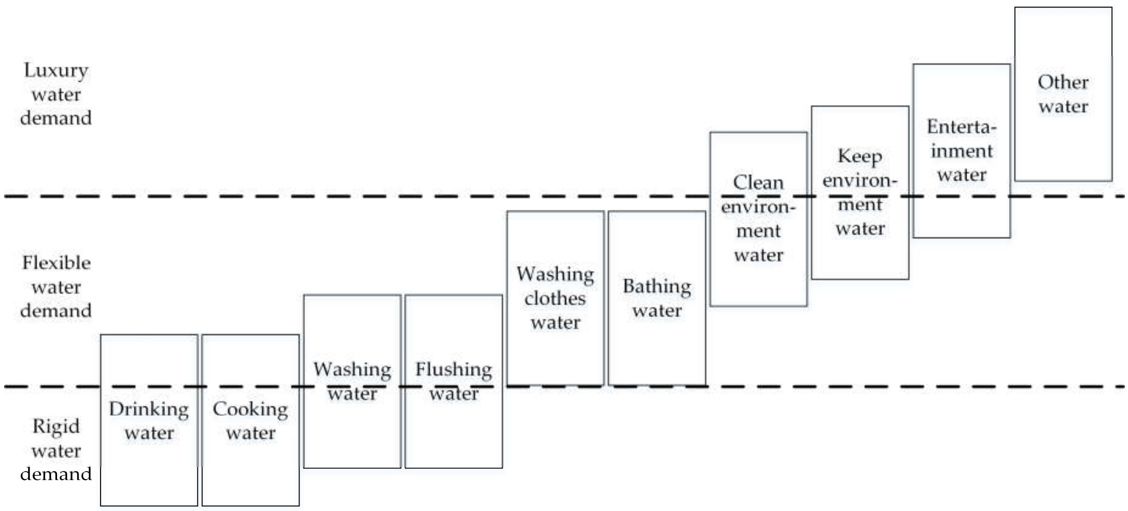

Figure 5. The different types and representations of household water demand of different levels. Note: The height of the rectangles in the figure merely represents the water demand across different categories and does not represent the actual quantities of water demand. The black dotted lines represent the separation of different levels.

Equation (11) is the general equation for household water demand, while the household water needed on different levels could be derived through the adjustments of coefficients such as $\alpha_{k,j}$ and β_k.

Rigid water demand are the lowest level and the most basic demand of residential households pertaining to water resources, and the fulfillment of rigid household water demand is a basic human right. Rigid water demand should be prioritized in the allocation of water resources, even under special circumstances, such as preparations for war or emergencies. Rigid water demand include water for drinking, cooking, washing, and toilet flushing, while water for bathing, laundry, and home cleaning could be appropriately considered to fall into this group as well. As such, in order to simplify the computations, the $\alpha_{k,j}$ coefficients for drinking water demand and cooking water demand are close to 1; the $\alpha_{k,j}$ coefficients for washing water demand and toilet flushing water demand are approximately 0.5; and the $\alpha_{k,j}$ coefficients for the water demand for bathing, laundry, and home cleaning are between 0–0.2 in the computation of rigid water demand. Furthermore, in consideration of influencing factors such as "water that is used for various purposes", the reuse of water, and the pipeline leakage rate, the β_k value could be set at approximately 0 or even negative.

Flexible water demand generally includes categories of water demand other than those for drinking and cooking, whereby the adjusted $\alpha_{k,j}$ and β_k coefficients could be used for computations based on the socioeconomic development of the area in question. In principle, the $\alpha_{k,j}$ coefficients for washing water demand and toilet flushing water demand are approximately 0.5, and the $\alpha_{k,j}$ coefficients for water demand for bathing, laundry, and home cleaning are between 0.2–1.0, which is a rather high range due to the influencing factor of the pipeline leakage rate.

Luxury water demand refers to the water demand beyond the reasonable quantity of water demand, and theoretically, there could be an element of luxury water demand in all types of water consumption behavior. As different areas have different socioeconomic developmental standards and the management standards of water demand differ from area to area, the luxury water demand also differ in terms of area and stages. In the actual computations, the $\alpha_{k,j}$ and β_k coefficients of various categories were determined by comparing the advanced water consumption standards of similar areas or obtaining the luxury water demand by deducting the quantity of reasonable water demand from the total quantity of representational water demand.

Assuming M is a person's daily representational household water demand, rigid household water demand are approximately 0.2–0.3 M, flexible household water demand are relatively higher at 0.4–0.7 M, and luxury water demand are approximately 0–0.4 M. With socioeconomic development, rigid demand are generally stable and may experience slight growth; flexible demand could experience rather huge changes in terms of either reductions or growth, while luxury demand should gradually be reduced to 0.

3. Results and Discussion

3.1. Design of Observations and Experiments of Household Water Consumption

Currently, water meters are generally used to measure the household water consumption in Chinese cities. However, most of the time, only the total water consumption quantity is recorded, and there is no way to measure the water consumption for different categories. To observe the water consumption quantities of urban households in terms of the different categories, the study implemented the following monitoring experimental methods: we installed automatic online flow meter monitoring systems on the various household water outlets (taps and shower heads) and prepared a record table of water consumption categories that household members were made to fill in whenever they performed a water consumption activity. These records were then integrated with the monitored times and the water quantity readings on the measurement devices in order to compute the monitored water consumption of different categories.

The monitoring methods mentioned above were carried out according to the specific procedures below:

1. A survey was conducted on urban household members and water consumption facilities, and the number of water outlets was ascertained.
2. The possible water consumption categories were listed out, and a water consumption record table was prepared.
3. Based on the household water supply network and water outlets, a liquid turbine flow meter was installed by connecting a hose to each water outlet (the liquid turbine flow meter transmitted

signals to a paperless recording system in order to create an online monitoring measurement system). Codes were then assigned, and high-frequency monitoring was performed on the pipe flow of the different water outlets. The monitoring results were then automatically recorded by the measurement device (in the form of paperless records) and were stored inside the memory card within the device.

4. Each water outlet was labeled with the possible water consumption categories, and as much as possible, the same water outlets were used for the same water consumption category.
5. To differentiate among the water consumption monitoring of different categories, the residents were requested to record the rough timing or time frame of water consumption. In principle, they were requested to record the details of every water consumption activity and to fill in the record table.
6. During the monitoring process, the measurement devices were checked every seven days in order to ensure the accuracy of the timings and readings.
7. The monitoring experiments were carried out in a continuous manner or based on representative time frames of different annual seasons. Each monitoring experiment lasted for at least 20 days.
8. For situations in which there was a reuse of water (such as using the same water basin to wash two different types of vegetables as indicated by the timing in italics *(07:15)* in Table 1), the same monitored time could be filled in repeatedly in the record table. For situations in which water was used for various purposes (such as when water previously used for face or hand washing was collected for toilet flushing, as indicated by the timing in bold (**07:30**) in Table 1), the monitored time could be filled inside the water consumption records of another category. For water collected in specific water collection devices (such as buckets with marked scales; please refer to Figure 3; recorded as ***"2 water collection buckets"*** in Table 1), the actual time of the water consumption activity was to be recorded separately later.

Table 1. Records of household water consumption categories.

No.	Category	Serial Number of Corresponding Monitoring Device	Time of Water Consumption Activity	Remarks
1	Drinking (tap water, boiled water, purified water, etc.)	(1)	07:10, 18:00, 21:00	
2	Cooking (washing vegetables, cooking, washing pots and plates, etc.)	(1), (2), (7)	07:15, 07:15, 07:45, 12:00, 12:30, 18:00, 19:30	
3	Washing (washing fruits, washing milk bottles and toys, washing hands, washing faces, brushing teeth, washing feet, etc.)	(1), (4), (7)	07:05, **07:30**, ...	
4	Toilet flushing	(6)	07:02, 07:25, **07:30**, 08:05, ...	**2 Water Collecting Buckets**
5	Laundry (hand wash, machine wash, etc.)	(3),(4), (5), (7)	18:30	Machine wash
6	Bathing (bathing, etc.)	(5), (7)	20:30, 21:30	**2 Water Collecting Buckets**
7	Home cleaning (mopping, wiping, cleaning the fridge and cooker hoods, etc.)	(2), (4), (5), (7)	20:00	Mopping
8	Home maintenance (humidification, water consumption of pets, rearing fish, etc.)	(1)	22:00, 22:05	2 Humidifiers
9	Watering plants (indoor plants, outdoor garden, etc.)	(1), (2)	——	No such activity today
10	Washing cars	(5), (7)	——	No such activity today
11	Sports and recreation (water-based toys, children's pool, etc.)	(5), (7)	——	No such activity today
12	Others	——	——	No such activity today

3.2. Household Water Simulation Computation

Based on the experimental design above, we chose three grades of cities to observe their household water consumption processes. They are Beijing City (the capital city of China, first-tier city), Xi'an City (the provincial capital of Shaanxi, second-tier city), and the Yangling District (county-level area in the

Shaanxi province).The observational data used was real-time data that was recorded every day and computed based on summarized monthly data. The computational methods mentioned above were then used for the computational simulation of different household water demand categories. Table 2 shows the empirical coefficient $\alpha_{k,j}$ and the correction coefficient β_k of household water demand in different categories and on different levels. Figures 6–8 show the results of the actual value and the simulated value.

Table 2. The empirical coefficient and the correction coefficient of household water demand.

Water demand	$\alpha_{k,j}$							β_k
	Drinking	**Cooking**	**Bathing**	**Laundry**	**Flushing**	**Washing**	**Cleaning**	
Rigid	0.98	0.95	0.18	0.13	0.47	0.55	0.05	0
Flexible	0.02	0.05	0.74	0.78	0.53	0.45	0.67	0.08
Luxury	0	0	0.08	0.09	0	0	0.28	0

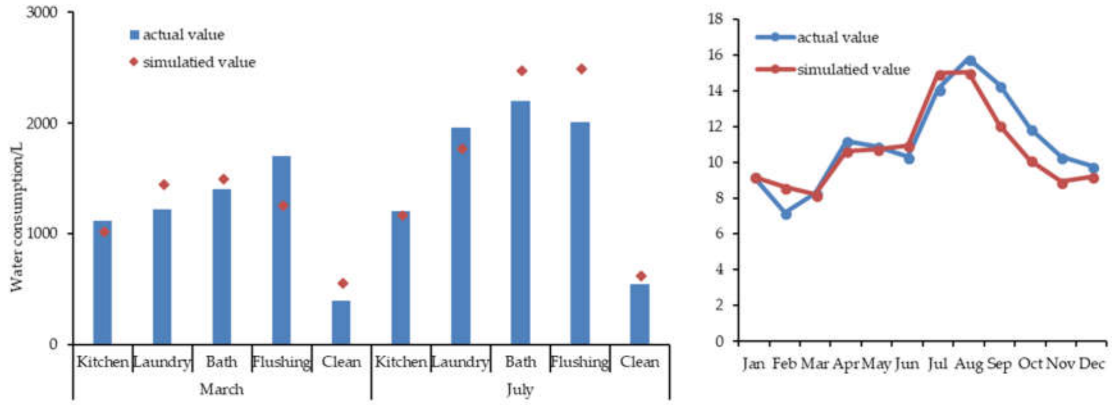

Figure 6. Comparison of actual values and simulated values of household water consumption in a Beijing City household.

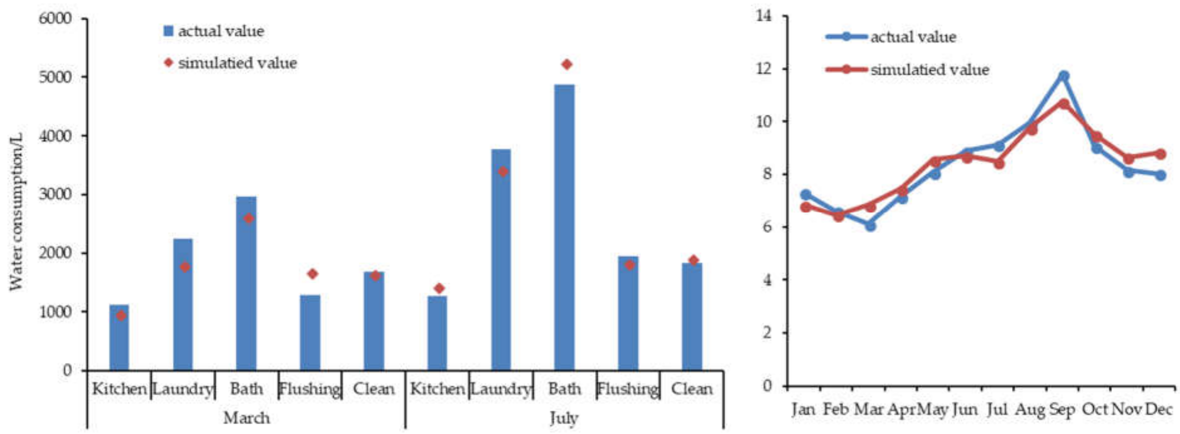

Figure 7. Comparison of actual values and simulated values of household water consumption in a Xi'an City household.

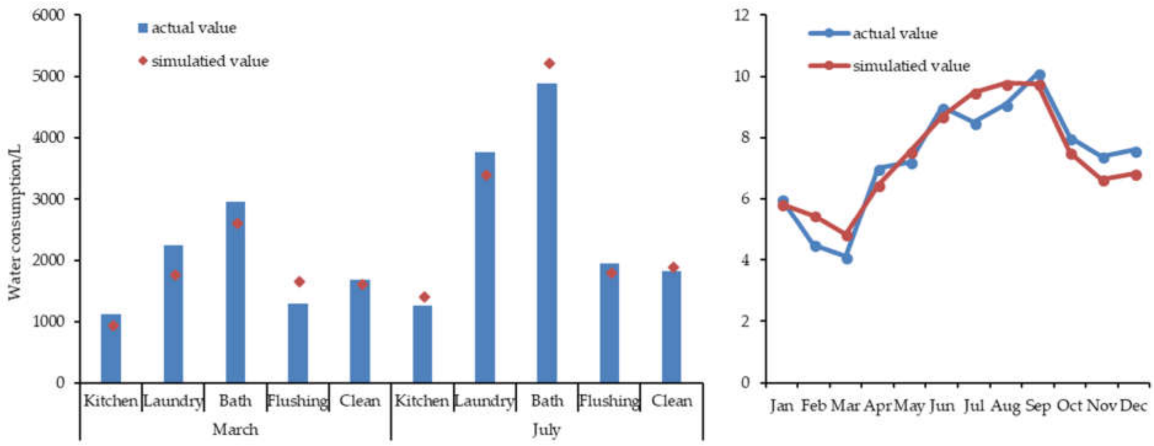

Figure 8. Comparison of actual values and simulated values of household water consumption in a Yangling District household.

The findings show that during the 2016 simulation period, the monthly simulation computations of the households in Beijing, Xi'an, and the Yangling District matched those of the actual measured results rather well, and the simulation results could effectively reflect the time-based change trends of household water consumption. Meanwhile, the simulation results of different water outlets and the actual values for typical months were not as promising. This is because the behavioral patterns of water consumption among residents were overly irregular, leading to huge differences in water consumption among water outlets. On another note, as the overall time change trends were influenced rather greatly by seasonal changes, the accuracy in the time change simulations were rather high. Through comparing the different simulation results of different households, we found that the model simulation results of the Yangling District household was the best, with the highest error rate being 14.7% and the lowest error rate being 3%.

Generally, the computational methods above were rather accurate and could be applied for the simulation and predictions of different household water demand, as well as different household water computations and predictions for different levels of household water demand.

3.3. Discussion

The limitations of the study include the following:

1. Due to the limitations of experimental devices, this study conducted experiments on only three urban households in Beijing, Xi'an, and Yangling to observe their household water consumption. Hence, the selection of study samples was inadequate. Furthermore, since the weather conditions and residential water consumption habits in the south and north are rather different, this study failed to perform a comparative analysis on the household water consumption of southern and northern urban households. On another note, this study observed only urban households and did not conduct observations and simulation verifications on the household water consumption of agricultural households.
2. There was a rather weak standard of verifying the computations of household water demand, whereby the computations had relatively low calibrated parameters because only certain parameters were calibrated. As such, the study lacked overall verification in terms of computational parameters.
3. Since this paper conducted simulations on only household water consumption, future studies should conduct simulation research on the entire water cycle of urban household units, establish a whole process method and a model of household water use, consumption, and drainage, and uncover the complex system of household units in terms of water cycle laws and characteristics. Exploring the said areas would help create a new set of tools for the prediction of urban household water

consumption and the fine-tuning of urban water resource management, and will also provide useful information to the decision makers of the water supply systems.

4. Conclusions

Based on the categorization and the characteristic analysis of household water, this paper used Maslow's Hierarchy of Needs to establish a level and grade theory of household water demand, whereby household water is classified into three levels (rigid water demand, flexible water demand, and luxury water demand) and three grades (basic water demand, reasonable water demand, and representational water demand). An in-depth analysis was then carried out on the factors influencing household water demand, whereby equations for different household water categories were established and computations for different levels of household water were proposed. Finally, observational experiments on household water consumption were designed, and observations and simulation computations were performed on three typical households.

The results show that in the simulation period of 2016, the simulation computations of the three typical households were in agreement with the measured household water consumption, reflecting the changing trend of water consumption with time effectively, while the simulation results of water consumption and the actual value of different terminals in typical months were general. By comparing the simulation results of different typical households, the simulation results of the Yangling District was the best, with the highest error rate being 14.7% and the lowest error rate being 3%. The results verify the scientific nature and rationality of the computation of household water demand.

The results further enrich and develop the water demand prediction theories, which is of great theoretical and practical significance for the scientific prediction of future water demand and the realization of the improved urban water resources management.

Author Contributions: Wenxiang Pan, Baodeng Hou and Ruixiang Yang conceived and designed the methods and model; Jianhua Wang and Yong Zhao conceived the theory; Wenxiang Pan, Xuzhu Zhan and Wenkai Tian carried out the experimental observation; Wenxiang Pan, Baoqi Li and Yuyan Zhou analyzed the data; Xuerui Gao, Weihua Xiao and Jianhua Wang contributed analysis tools; Baodeng Hou and Ruixiang Yang wrote the paper. Wenxiang Pan and Baodeng Hou contributed equally to this work and should be considered co-first authors.

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