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ANALYSIS OF THE WATER USE IN DIFFERENT TYPES OF BUILDINGS

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ABSTRACT
The analysis of the water use of the different consumers is an important issue for the proper design, performance and management not only for the water supply and sewerage systems in the buildings, but also for the urban water infrastructure as a whole. Water use changes with time due to many climatic, socio-economic, cultural and technical factors and is tightly connected with the development of the society and technologies. When the change becomes substantial, there is a need of upgrading and verification of the design parameters and methods, but also the construction practices and maintenance requirements as well as the corresponding regulations, so that they become adequate with current and future development. Analysis of the different methods characterizing the water use in the buildings on quantative basis as well as the determination of its seasonal, daily, hourly or shorter period of time variation is made. The advantages and disadvantages of water demand mathematical models are discussed and on that basis of that, a statistical method for estimation of the parameters of hybrid stochastic-regression water demand model is recommended to be used. The approach gives contemporary theoretical basis of water demand on different spatial and temporal scales and can be used for analysis of water consumption not only in the different types of buildings but also in the settlements.

Keywords: *Statistical method, Stochastic-regression model, Water demand, Water use analysis*

1. INTRODUCTION

The analysis of the current water use for estimation of future water demand of the different consumers is an important issue for the proper design, performance and management not only for the water supply and sewerage systems in the buildings, but also for the urban water supply infrastructure as a whole. Water use changes with time due to many natural, socio-economic, cultural and technical factors and is tightly connected with the climate, development of the society and technologies. When the change, due to any of the factors, mentioned above becomes substantial, there is a need of upgrading and verification not only the design parameters and the sizing methods, but also the construction and management practices and maintenance requirements. And because the water use is specific for every country, it is not recommended to adopt foreign water demand norms and sizing methods, without checking their adequacy. There are different users of information for the water demand and the way they look at it.

The designers are interested from the methods for estimation of the average and peak water demands, as well as and daily demand patterns of the different buildings.

Water supply companies need wider range of information, including economic and price data. In addition to the design data, which is necessary for diameters network and equipment sizing, they are interested also in long-term evaluation of the water supply system capacity. Their short-term and long-term investment programs are tightly connected with that, as well as the efficiency of their management and maintenance practices.

The building maintenance companies are interested in the current and future capacity of the plumbing systems and energy efficiency, as well as in daily demand patterns, peak flows etc.

The range of the tasks becomes wider with development of hydraulic simulation software and their incorporation in decision making processes and smart buildings and smart cities concept.

Theoretical understanding for the process of water demand is the basis of any analysis of the water use in the different types of buildings. The method for description of the water demand depends on the specific purpose for which it is developed.

2. THEORETHICAL MODELS

2.1. Classification of water demand models

The theoretical models, describing water demand can be basically classified as follows:

i. depending on the type of the objective:
   - for buildings;
   - for settlements;
   - for industry.

ii. depending on the time interval:
   - monthly(seasonal);
   - daily;
   - hourly;
   - less than 1 hour(30 min; 15 min, 5, min, 1, min, 1 s.).

iii. depending on demand value:
   - minimum water demand;
   - average water demand(daily, hourly);
   - maximum water demand (design flow ratec- daily, hourly, less than 1 hour).

iv. depending on the application:
   - for design - dimensioning of pipes and water equipment (peak flow rate estimation): sizing of the pipes; water tank and water heaters volume estimation, booster pumps capacity estimation etc.;
   - for planning (short and long-term);
   - for management of the water infrastructure facilities (energy efficiency, simulation of different scenarios).

v. depending on the used mathematical method:
   - deterministic;
   - autoregressive: autoregressive integrated moving average (ARIMA) and autoregressive integrated moving average model with exogenous input variables (ARIMAX), etc;
   - simulation based models (Monte Carlo simulation).
   - based on artificial neural network (ANN);
   - stochastic;
   - combined (hybrid) – wavelet-bootstrap-NN, stochastic-deterministic; ANN-stochastic, ARIMA-ANN etc.

In most of the cases, the models involve highly aggregated (urban distribution network) data, for particular time interval (day, hour) and particular application.

The objective of the present paper is to review the theoretical water demand models and to propose a suitable for short-term analysis of the water use in different types of buildings from the point of view of their applicability to describe the demand for different time intervals and covering different aspects (design, management) with acceptable accuracy.

2.2. Theoretical approaches

Long-term forecasts are generally annual and decadal, while monthly forecasts, with up to 24 months sometimes are classified as medium term. Long-term forecasts usually involve economic, demographic, and future climate change variables, with the aim to foresee the development usually for planning and design of water system infrastructure.

The water demand in the buildings basically can be divided into domestic and non-domestic. The non-domestic water demand is associated with water use in the industrial buildings for production purposes.

Domestic water demand is connected with human life cycle activities in the residential, public (shops, offices, hospitals, schools etc.) and industrial buildings. Domestic water use includes: toilet flushing, bathing and showering, laundry, dishwashing and some less frequent uses like cooking, drinking, gardening, car washing, etc.

The water use in the buildings is influenced by many factors, which are not static but complex and dynamic. Models including these variables could explain to certain degree the uneven special and temporal water use in the buildings. Identifying the meaningful variables is a substantial task itself and not easy to be solved.

Economic variables like water price and population income are important factors, but also some socio-demographic variables like, size and characteristic of households, age and gender of the users also give considerable input in water demand variation.

Other group of variables comprises cultural and educational level of the users. Climatic factors like temperature, humidity, and rainfall data appear to be another set of variables that cannot be neglected in the mathematical models.

All these factors give very complex structure of the models and require monitoring and forecasting their behavior in the end water demand. The collection of the input data is difficult and time consuming. At the same time the gathered variables information is temporally valid and with suspicious accuracy.

Typical approach for modeling the water demand involving the mentioned variables is multiple regression analysis. A lot of research in the past is based on this method using different mathematical models such as:

- multiple regressions, ordinary least squares regression, weighted regression (House-Peters, 2011);
- projection pursuit regression (PPR), multivariate adaptive regression splines (MARS), support vector regression (SVR) (Herrera M., 2010).
-

The application of regression method for estimation of hydrological data with machine leaning technique and the use fuzzy clusters is proposed by Shrestha (Shrestha D., 2007).

More detailed short term forecasts include not only historical water used data but also weather and calendar variables (such as weekday, hour of the day and presence of holidays). As the most important predictive variables that influence water demand are determined to be the temperature, the relative humidity and the hour of the day. Weather variables appear to be most sensitive for outdoor water demand. (Brentan B. M., 2017)

Some of the models separate water demand into two components: weather-insensitive base use (winter or indoor) and weather-sensitive seasonal use (summer or outdoor).

The regression based models examine climatic effects on demand and incorporate both temporal and subject-based variability into coefficient estimates. The models are mathematically clear and easy to be used, but there are some basic disadvantages, which limit their application for solving different tasks:

- based on long term aggregated time series experimental measurements;
- validity for a comparatively short period of time, after which they need verification;
- the data is aggregated for urban areas and contains a lot of uncertainties;
- assumptions for independence of the variables;
- difficult to determine the correct functional form of the model;
- conventional models may underestimate water use response to climate variables because of the influence of stochastic events on seasonal use;
- involve considerable resources and time and finally doesn’t give the expected accuracy etc.

Another approach based on time series data analysis, used for short-term forecasting of water demand is the autoregressive integrated moving average (ARIMA) method (Alvisi S., 2007) and Markov chain (Gagliardi, et al., 2017), applied for urban areas. The autocorrelation forecasting models account for the autocorrelation in the water demand time series, based on the previous period of time (day's) water demand as an independent variable. The disadvantages are associated with:

- the data aggregation at large spatial scales;
- difficulties to determine a priori correct model form and parameters;
- difficulties with its application on different time intervals less than 1 day etc.

During the last decade, models based on artificial neural network (ANN) are developed: traditional ANNs (Adamowski, 2008), dynamic ANN (Ghiassi M., 2008), hybrid ANNs-wavelet analysis-based ANNs (WNN) and bootstrap-based ANNs (BNN) (Tiwari, 2013).

Most of the models, mentioned above are applied for large scale water distribution networks mainly for short-term-forecasting, generally weekly, daily, hourly water demand in distribution urban water supply systems.

Their main characteristics are: effective for forecasting short-term demand; alternative to traditional linear modeling approach; can explicitly analyze nonlinear time series data; minimize the relative error etc. As main disadvantages can be pointed out the following (House-Peters, 2011):

- complex data;
- computationally intensive training and testing requirements;
- lack of justification of the results;
- sensitive to misspecification error ect.

Comparisons of the results, received from applying different mathematical models, have shown that the best performance is achieved by support vector regression model (SVR) followed by multivariate adaptive regression splines (MARS), projection pursuit regression PPR and Random forests. ANN variants haven’t shown good results (Herrera M., 2010).

It is not easy to come to agreement for the best mathematical approach, due to the different:

- conditions under which the research is done, sometimes with dynamic behavior of the input variables;
- applications of the models, for which they are developed;
- experience and mathematical knowledge of the researchers;
- lack of clear theoretical interpretation of water demand as process etc.

Most of the methods described above, refer to urban daily and hourly water demand modeling using highly aggregated data. The uncertainties of the results, that often are received can be associated with specific for each urban area aggregated data and lack of clear theoretical understanding of the water demand as a whole.

When referring to building water supply systems, besides the daily and hourly water demands, most interested are the peak flows for much smaller intervals of time, reaching 1second. Some of the approaches for estimation of the peak demand for a period of time equal to and less than 1 hour are similar to those for urban water supply systems, but there are also approaches, which are completely different.

Recent review of the demand models for the water supply and drainage systems in buildings including Baysian approach was done by Wong (Wong, et al., 2018). He classifies the approaches of demand models for water systems in buildings into three main types: deterministic; probabilistic and simulation.

Deterministic approach, based on experimental data of water use is widely used for estimation of peak flows in the buildings (design flow rate). As the allowable failure rates in these models are constant, the design flow rates are fixed values. These models are commonly used in design guides and standards for specific system designs due to their simplicity and small number of parameters (number of fixtures and specific fixtures flow rates). But there are also some basic disadvantages, that limit their application only for modeling of the peak flows: validity under specific temporal scale (time interval); specific for each type of buildings; some of them don't account for the number of the users in the building etc.

The methods reflecting the stochastic character (probabilistic) of the demand in the buildings can be sub divided into three main groups: discrete probability distribution based; continuous probability distribution based; combined(hybrid)-stochastic-regression or other.

Probabilistic approach based on queuing theory and including discrete random variables (discharge duration of the plumbing fixtures, number of fixtures of each type or "fixture units", unitary flow rates) is applied for estimation of the peak flows in the buildings. It is associated with the studies of Hunter (1940), Webster(1972), Courtney, Konen(1980), Murakawa(1989), Wistort(1995) (Konen, et al., 1993; Wong, et al., 2018; Buchberger, 2018). Little is known about some studies using the same probabilistic approach outside the English speaking world, like those of Kursin(1936), Shopenskii (1960), Dobromislov (Dobromislov, et al., 2007), Hadjiev(1955).

The predominant methods based on discrete probability density functions apply:

- Binomial distribution – Kursin, Hunter, Webster, Konen, Wistort
- Poisson distribution – Hadjiev, Murakawa etc.

The disadvantages of these models are connected with implementing different assumptions for discharge fixtures duration, functions for estimation of discharge fixtures flows, fixture usage is accepted to be independent variable in time, the parameters of the model don't have physical meaning, which makes problematic their experimental evaluation etc.

The methods based on stochastic process theory accept the water demand can be described by continuous distribution functions with Normal (Alitchkov, 1998), Gamma, Erlang, Exponential and Beta (Wong, et al., 2018; Konen, et al., 1993) or Log-Normal, Log-Logistic and Gumbel distribution (Gargano, et al., 2017).

The water demand is modeled, either as very complicated process depending on specially and temporally varying factors or as grey or black box with specific input data based on certain assumptions and functionalities. The combination of stochastic process modeling and deterministic technique can considerably simplify the efforts to find the compromise between accuracy, simplicity and physical phenomenon.

Statistical mathematical model applied for different time scales gives logical theoretical description of stochastic characteristic of water demand. This approach, applied for modeling the flows in the buildings using hybrid stochastic-deterministic is suitable theoretical basis for mathematical explanation of water demand (Alitchkov, 1998). It has the flexibility to describe domestic water demand in different types of buildings, based on few parameters and can be applied for modeling the flows on different time intervals - day, hour, less than 1h hour (30min, 15 min, 5 min, 1 min, 10s, 1s). The mathematical model has comparatively simple structure, giving clear understanding for the process of water demand dependent from the human life circle in the different types of buildings.

Water demand is considered to be created from three non correlated components (Verbitsky, 1993):

- harmonic, reflecting the repeating variation of the demand during the day;
- centered hourly stochastic water demand, reflecting the hourly difference from the harmonic process;
- centered for less than 1 hour time interval water demand, reflecting the difference between the stochastic hourly and less than 1 h time interval demands.

The subject of the present paper is the identification of necessary disaggregated by water user class data and the analysis, which is to be performed in order that the sub-models (for the different types of buildings) are determined with the aim to implement combined statistical approach not only for the building water use data processing but also for modeling of flows on larger scale. As a basis of this research are used previous studies and current large scale investigation of water demand in Sofia municipality, which involves 310 buildings of different types during 3 years period of time.

3. DATA STRUCTURING

The harmonic component of the demand indirectly reflects the socio-economical and demographic characteristics of the users, such as type of the building; sanitary equipment level; type and degree of maintenance; consumers' water use culture; price of water, etc. All these factors don't vary dramatically with time and can be periodically updated operatively determined using statistically disaggregated data by type of buildings, time interval and level of maintenance.

3.1. Types of buildings

The buildings are divided into different types, according the national legislation and water demand regime as follows:

- residential , sub dived into 6 sub-groups;
- kindergartens, schools and universities, sub-divided into 5 sub-groups;
- hospitals and polyclinics, sub-divided into 3 sub-groups;
- restaurants and clubs, sub-divided into 3 sub-groups;
- sport's buildings and complexes, sub-divided into 3 sub-groups;
- cinemas and theaters;
- hotels, sub-divided into 2 sub-groups;
- shops, sub-divided into 2 sub-groups;
- administrative and office buildings;
- hairdressing salons;
- dormitories.

3.2. Time interval water use data

The metered water use data is structured in such a way, so that it corresponds to the estimation of the theoretical model parameters:

- analysis of seasonal effect - season water use data;
- analysis of daily water demand - daily water use and pressure time series;
- analysis of the daily water demand patterns - hourly water use and pressure time series;
- analysis of the shorter than 1h (τ) water uses variations - 1 min water use and pressure time series.

Each data set serves particular analysis and parameters estimation. The most detailed data is short-term water use data ($\tau=1min$), which is the base for the next cumulated data sets.

3.3. Level of maintenance of the plumbing systems

The level of the maintenance of the plumbing system is introduced for evaluation of the "water losses" in the buildings due to leakages from the pipes, joints, broken and forgotten in open state fixtures. The analysis of the water demand in the different types of buildings would be unrealistic if the raw data including water losses is used. This criterion influences considerably the accuracy of the water demand model if not considered and is especially important for the public buildings, where the losses appear to be bigger than those in residential buildings.

The water losses $q^i_{\tau(t)}$ for day i are determine per time interval $\tau \leq 1$h , using the following equation:

$$q^i_{\tau(t)} = b_i \int_0^\tau P_{ef(t)} dt \quad \text{,dm3/min} \qquad (1)$$

where, ***Pef(t)*** is the average pressure in the building water supply network during time interval (τ), which may vary considerably during the day.

$\boldsymbol{b_i}$ - parameter, which is determined on daily basis (for each day i)by analyzing the night short-term water use for a period without losses.

An indicator for the maintenance level can be either the losses, expressed as % from the daily water use or specific water losses per fixture. Table 1 shows proposed scale for the level of maintenance based on relative water losses. The buildings are classified into four types(the values are indicative).

Table 1. Disaggregated data by level of maintenance

Maintenance level	Water losses, %	Description
A	0-5	Very good (high) level of maintenance
B	6-15	Good level of maintenance
C	16-25	Poor level of maintenance
D	>25	Very poor/lack of maintenance.

The influence of the water losses on the water demand and the daily patterns for the buildings from class B, C, D is substantial and has to be considered. That is why for further analysis of the water demand regime, water losses are subtracted. Some of the received so far results for the water losses in residential and public buildings are shown on figure 1.

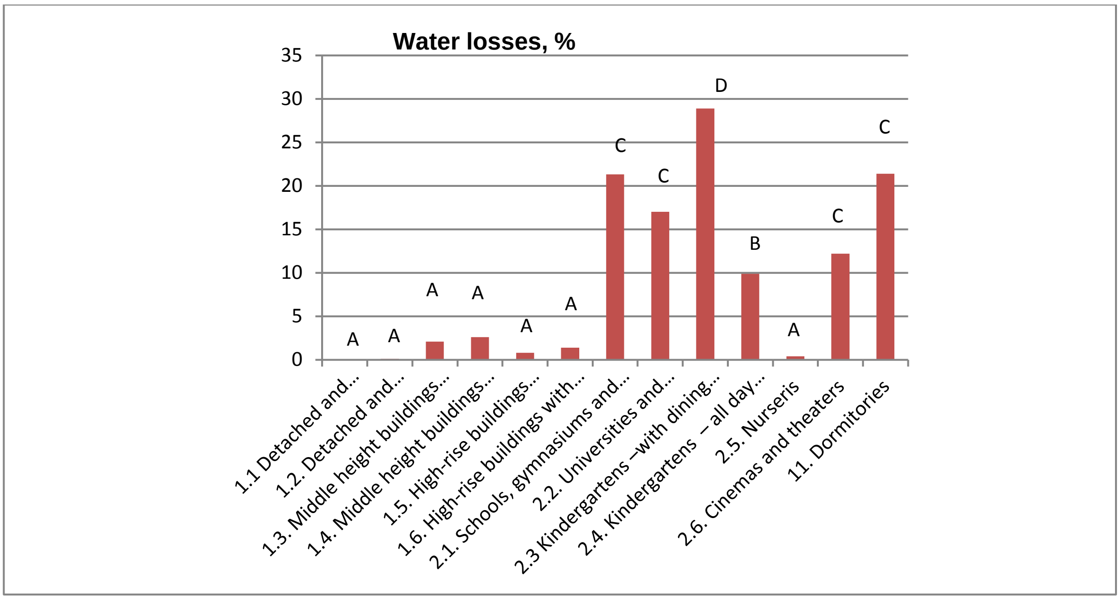

Figure 1. Water losses in different types of buildings

4. STATISTICAL ANALYSIS

3.1. Water demand at different time sections

The statistical analysis of the water use in the different types of buildings shows, that Lognormal distribution gives good theoretical agreement with the measurements at the different time sections as shown on figure 2, 3, 4. The received results coincide with the conclusions, made by (Gargano, et al., 2017).

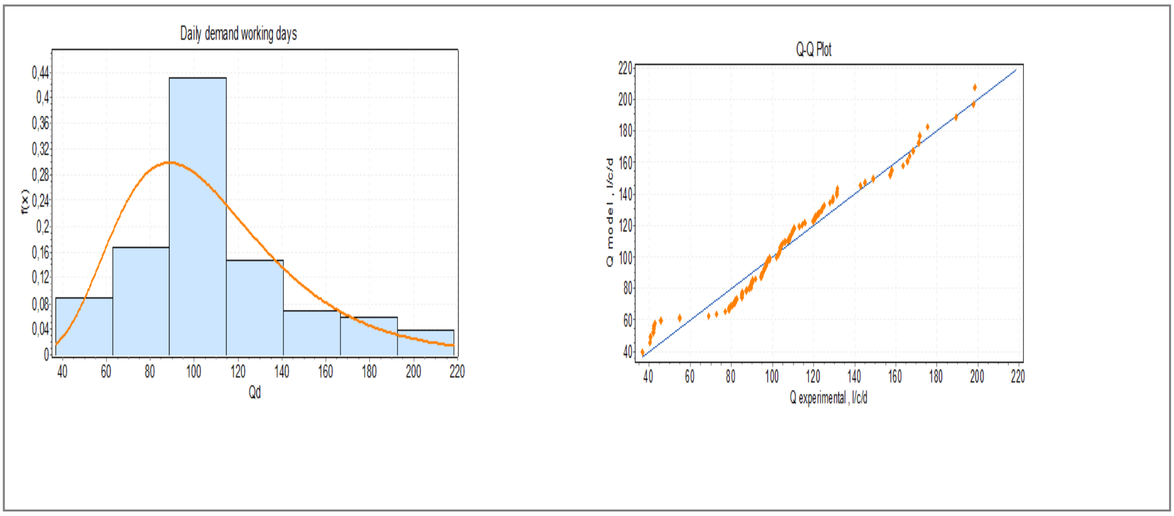

Figure 2. Lognormal distribution of working days daily demands in student’s dormitories

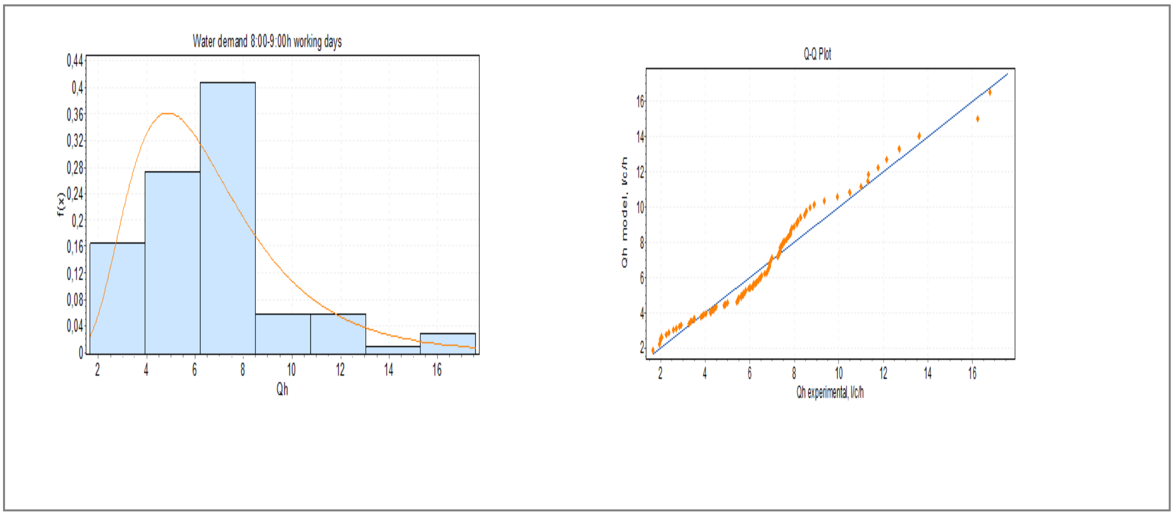

Figure 3. Lognormal distribution of working days hourly demands in student's dormitories

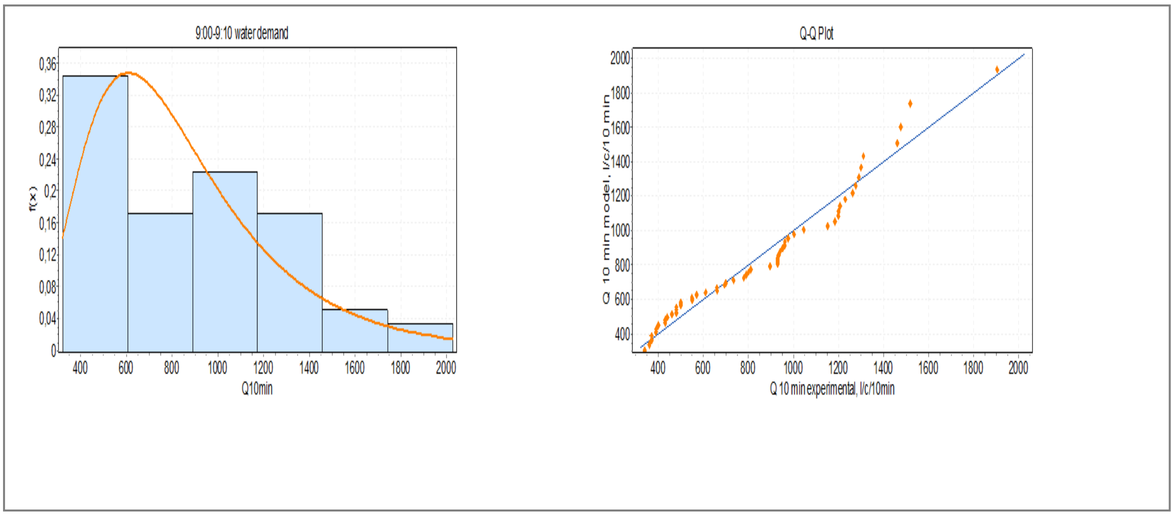

Figure 4. Lognormal distribution of working days 10 min demands in student's dormitories

4.2. Seasonal water demand influence

As written above, seasonal variation appear to be most sensitive for outdoor water demand. The influence of the weather variables, like temperature, relative humidity rainfall etc., which are usually used in regression analysis models can be expressed by harmonic seasonal process and can be statistically determined by processing the seasonal aggregated data set without losses.

The seasonal variation is characteristic to outdoor water demand for irrigation of grass areas and gardens around the buildings. Mostly influenced by seasonal effect is the demand of detached and semidetached residential buildings and less - the multistory and public buildings. As bigger their irrigation areas are, the bigger seasonal effect is.

4.3. Standardized water demand patterns

Daily demand patterns represent the harmonic calendar variation of the water demand, which is different during the work days and holidays and weekends. The hour of appearance of the daily peaks (morning and evening) differs between 1- 3 h. The daily demand patterns are determined statistically by processing the hourly water use data set for each type of the buildings and an example for one type of building is shown on figure 3.

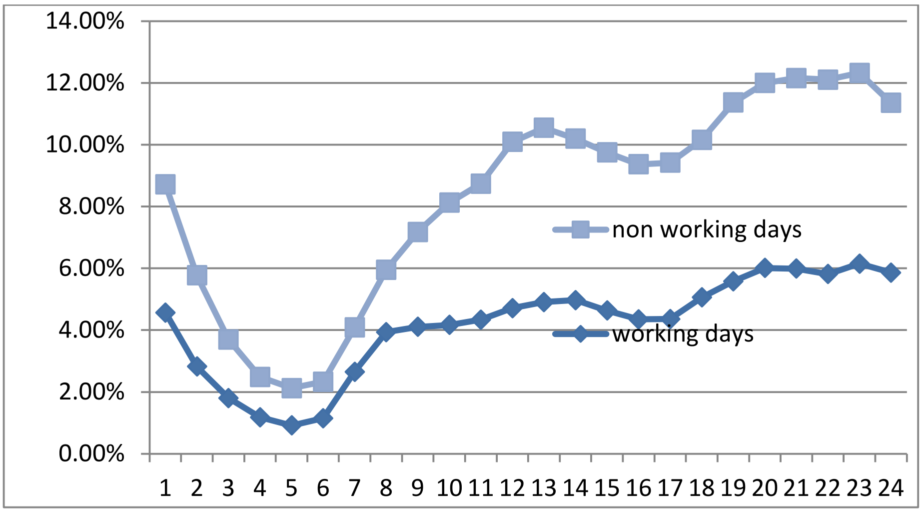

Figure3. Water demand patterns in student's dormitories

Peak water demands

The peak water demands in the building are associated with sizing procedures and shorter than 1 hour time interval, usually 1 s, determined with very small failure factor (0,01).

The aim of the present analysis is to determine the parameters of the mathematical models on the basis of the specific sanitary equipment of the buildings and the number of the inhabitants (water users).

The centered hourly stochastic water demand component appears as a deviation from the harmonic one and is represented statistically by its variance (Alitchkov, 1998). The stochastic component is shown on figure 4 as hourly difference from the harmonic component.

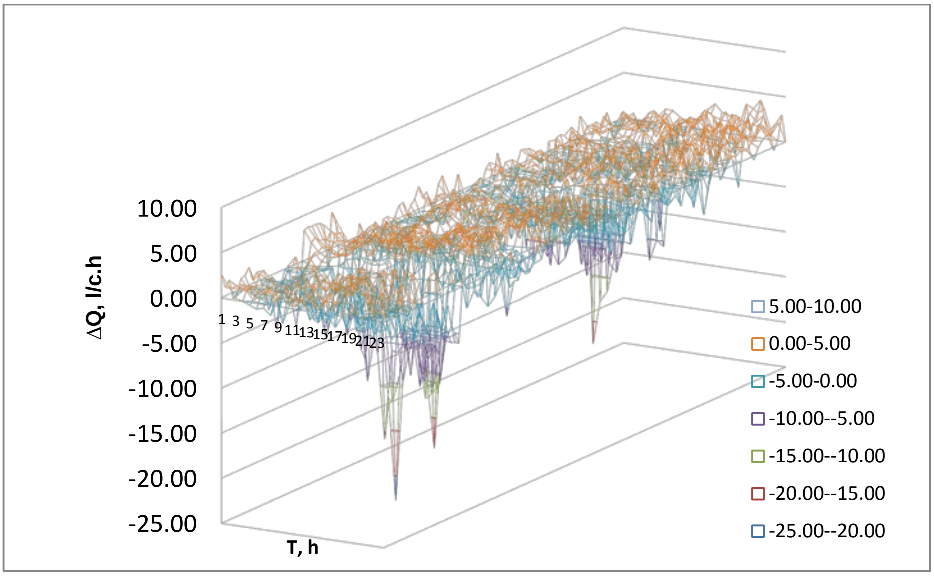

Figure 4. Stochastic hourly water demand in student's dormitories

The centered for less than 1 hour time interval (τ) water demand, reflecting the difference between hourly and τ time interval stochastic processes and is represented by its variance, $Var(Q_\tau^s)$.

The relationship between the statistical and physical parameters - the average hourly specific water demand per fixture unit ($\bar{q}$) and the number fixtures units ($\sum n$), can be determined using regression analysis or other mathematical technique: $M = \frac{Var(Q_h^C)}{Var(Q_h^S)}$, $F_\tau = \frac{Var(Q_\tau^S)}{Var(Q_h^S)}$. Results for the established parameters for schools are shown on figure5.

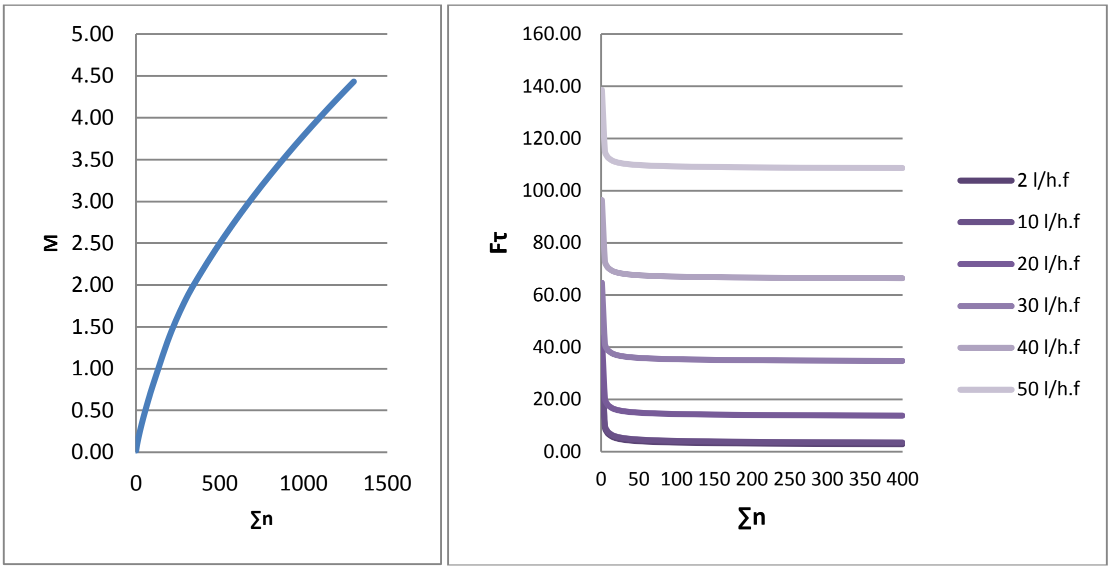

Figure 5. Regression model parameters for schools

5. CONCLUSIONS

Classification of different models describing the water demand is done according to: the type of the objective; time interval; demand value; application; used mathematical method. Analysis of the different methods characterizing the water use in the buildings on quantative basis as well as the determination of its seasonal, daily, hourly and shorter period of time variation is made. The advantages and disadvantages of the different mathematical approaches of water demand are discussed and on that basis of that, a statistical method for estimation of the parameters of combined stochastic-regression water demand model is recommended. The approach gives contemporary theoretical basis of water demand on different spatial and temporal scales.

Disaggregated water use method by type of the objective, level of maintenance of water supply system and time interval is proposed. The results show that Lognormal distribution gives good theoretical agreement with the measurements at the different time sections. Regression model parameters, which connect the statistical and the physical parameters, can be estimated rather easily on the basis of limited number indicators with acceptable accuracy. The proposed approach can be used for modeling the water demand not only in the plumbing systems of buildings but also in the distribution water supply systems of settlements. In combination with GIS information and remote water metering, it can be incorporated in the algorithms for modeling the water demand under different scenarios for development of smart techniques for buildings and cities.

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