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Properly allocating the urban water meter readings to the nodes of a water pipe network simulation model

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ABSTRACT

This paper presents an alternative approach regarding the spatial allocation of the actual water demand when developing the hydraulic simulation model of an urban water pipe network. This approach can be applied in cases where the customers' water meters are not georeferenced (usually the case in developing countries), reducing the computational time needed for the model's calibration increasing, thus the method's cost effectiveness. The simulation process takes into account the respective demand patterns of the various types of urban water uses, considering the water volume being lost through leaks/breaks occurring in the pipe network, as a competitive use. Each kind of water use is divided in its pressure-dependent part and its volume depended one. Both parts are introduced to the model. The water losses' diurnal pattern calculation method is also thoroughly presented. Kos Town (Greece) water pipe network is used to demonstrate the entire process. To prove its effectiveness, the results of the new proposed method were compared to Voronoi diagrams method's results and to field measurements.

Keywords: Water pipe networks; Hydraulic simulation models; Water demand allocation

1. Introduction

Hydraulic models can be used to analyze systems where demand and operating conditions are considered either steady state or time dependent. The actual level of the water demand is the driving force behind the hydraulic dynamics in a water distribution system (WDS). Consequently, it is crucial to estimate this level as accurately as possible in order to result in reliable simulation models. Nevertheless, the accurate spatial allocation of the water consumption is the most difficult but necessary goal to achieve while developing the model. Most existing relevant software packages use the spatial analysis capabilities of GIS software and databases, such as geocoded records of water meters. But this cannot be done when these water meters are not georeferenced (usually the case in developing countries). Proper recording of water losses, both in time and space, is desired. Since water losses in developing countries are a large part of the overall consumption, it is important to be further distinguished in their components (real losses, apparent losses, etc.). After developing the basic backbone of the network's

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hydraulic simulation model, its calibration follows usually by measuring pressure and flow rates at selected nodes [1]. Well-defined standards should be available to help decide/judge when a model is sufficiently calibrated or not. These standards vary depending on the model's intended use [2]. The discrepancy between field measurements and model calculations is mitigated by modifying the values of the pipes' internal roughness coefficients [3]. Incorrect estimation of these values, may result to misleading assessments regarding the pipes' "aging" factor, and thus to faulty forecasting of future pipe failures.

Deviations between the model's outcome and observed field data could possibly be due to major leaks, errors in water meter readings, faults in recorded sizes of pipes, or closed valves [4]. It can be easily understood that pipe roughness coefficients and water consumption referred to the model's nodes are mainly based on estimations in contrast to other parameters such as pipe length, diameters, and tank levels, which can be directly measured. To overcome this uncertainty factor, the method of adjusting the values of either the pipes' roughness coefficients or the estimated water consumption at nodes up to the point, that the pressure and flow values resulted by the model are in agreement with the actually measured ones, is preferred. One of the numerous attempts that took place over the years, regarding the level of accuracy in assessing pipes' roughness values, is the one of Colebrook and White [5], who developed a model reflecting the connection between the rate in which a pipe's carrying capacity decreases as the pipe grows "old." Although, in several cities around the world, full-scale pipe tests regarding the above matter took place [6] it is rather unlikely to develop an accurate model (reliably calibrated) to present the hydraulic operation of a real system [7] since pipes' roughness values are difficult to be precisely defined. It is generally recommended to categorize the pipes when calibrating the model due to the small set of field data observed [8]. The most precise approach of the actual water consumption allocation at nodes level results in a smaller extent of modification of the network variables, specifically of pipe roughness, in order to "bridge the gap" between model outputs and field measurements. If this distribution fails to be precise, the selected pipes' roughness values will noticeably differ from the real ones during the model's calibration stage. Whether obvious or not, the leaks of a network are mainly caused due to corrosion, erosion and debris built up [9]. Faulty estimation of pipes' roughness values results in improper evaluation of the pipes' aging elements, which leads to incorrect estimations of their carrying capacity. Incorrect estimation of this capacity leads in false future scenarios regarding potential failures and at the end to a distorted determination of the required preventive maintenance interventions needed and a non optimal (cost-effective) use of the available funds.

The implementation of all this process in a typical developing WDS has to additionally cope with many shortcomings and restrictions. Often the land uses are not fully defined in details, the actual WDS is partially recorded and the data of consumers' water bills are poorly updated. All these obstacles raise the question of "what procedures should be followed to maximize the benefit/cost ratio when applying the steps necessary to develop a WDSs simulation model?" Sometimes the practices followed to upgrade the operational level of a growing water utility are extremely costly and time consuming for the provided final outcome/result. There are several problems that have to be handled when trying to develop a WDSs simulation model, like the availability, quality, and reliability of data provided by the water utility. The aim of this study is to present the need of a new method of demand allocation (called spatial allocation of water demand at street level [SAWDSL]) to save time and money. The present paper also aims to demonstrate the entire process and the problems faced by applying the SAWDSL method to develop Kos Town WDS model.

2. Hydraulic simulation of the water demand in a WDS

2.1. Residential and commercial demand

2.1.1. Existing approaches regarding the spatial allocation of the water demand

The equations used to model a WDS are based on the simplistic assumption that water reaches the customers through the model's nodes, usually being far less in number compared to the actual service pipes connections existing along the pipeline. Various expressions have been developed to bridge the gap between the actual water use along the pipeline with the consumption appointed to the nodes of the simulation model [10,11]. To allocate the water demands to the nodes of the model, when the spatial data regarding the water meters are partial (or even lacking), Voronoi diagrams (or Thiessen polygons) can be used. Today, there are several base demand automated allocation strategies using GIS tools successfully. Although water utilities keep records regarding the water meters' readings, their reliability, in order to be used to simulate the spatial distribution of the water consumption, is questionable. The water meters spatial data is divided into three categories, depending on the advancement and evolution of water utilities: (a) those with low data reliability; (b) those with partially completed water meters information; and (c) those, which specifically point out the water meters' coordinates in a GIS. This lack of data can be faced by either multiplying the number of consumers assigned to a node by the per capita consumption [2], or by allocating the water demand based on the records of water meters. Nevertheless, it is necessary to carefully deal with uncertainties when it comes to the partially completed data. There are two main approaches (top-down vs. bottom-up) to overcome imprecision, both based on general mass-balance scenarios [2]. During the process of top-down demand allocation, the water volumes entering the network are defined (system input volume [SIV]) and then, after subtracting the big known consumptions, the remaining demand, is somehow, being distributed to the nodes. The first step of the bottom-up demand determination process is to appropriately cluster and match the water meter data to the nodes, to approach reality. Most processes used today, tending to be system-specific based on the data available, the resources for data-entry, and the need for demands accuracy [2], are a some kind of mixture or variation of both the top-down and the bottom-up concepts.

Assuming that there are complete GIS records available, strategies, such as meter assignment, meter aggregation, flow distribution, and point demand assignment [2], are methods of demand-dependent automated distribution, successfully utilizing GIS tools. Through meter assignment practices, the demand of the spatial referenced water meter is directly assigned to the nearest spatial referenced node, so that each node's base demand is composed of specific water meters' recorded water use. Meter assignment, comparing to more complex allocation strategies tend to be less reliable since the nearest node is defined by straight-line proximity between the demand node and the water meter. The principle of assigning all meters within a service polygon to a specified demand node (defining thus the service area of each node) works by charging meter aggregation. The strategy of flow distribution consists of distributing lump sum area water-use data among a number of service polygons (service areas) and, further, their associated demand nodes. In the polygon called lump-sum area, although the total (lump sum) water use of all the service areas (and their demand nodes) within it is measured, the distribution of the total water use among the individual nodes is undefined. The water use records for these polygons depend on data from pump stations, treatment plants or flow control valves, pressure zones, and meter routes. A GIS polygon forms the area for which a flow is known. There is one flow rate per lump sum area, and there can be no overlap or open space between these areas. There are two processes to divide the known flow of the lump sum area among the service polygons within this area: equal distribution or proportional distribution. The technique, in which a point demand assignment strategy is used to directly assign a demand to a node, is primarily a manual operation. It is used to assign water users, such as large industrial or commercial users, to the demand node serving such a consumer.

In most developing countries, where water meters' spatial data are either incomplete or even lacking, there is tendency to apply combined techniques, depending on the quality and quantity of existing data, in order to better cluster and match water meters to nodes. In case of incomplete spatial data, the total consumption is divided in subgroups, each related to a respective group of nodes. Exploiting the case of flow distribution practice, an effort is given to drive each subgroup to its related node according to the equal or proportional allocation. In case of proportional distribution, either by area or by population, the lump sum flow is divided among the service polygons. As the percentage of one of these two attributes grows bigger, the percentage of overall flow that will be assigned to that service polygon increases. When there is no reliable data in hand, the well-known Voronoi regions are used to specify demand allocation by dividing the area served into a number of regions. First, a set of points (called sites, seeds, or generators) is defined and for each site, a relevant region is formed, consisting of all points closer to that site than to any other. In some cases, a specific combination of demand allocation methods may be recommended as the most helpful technique (e.g. to account for the unaccounted-for water) [2].

2.1.2. SAWDSL: an approach to allocate the water demands

The spatial demand allocation based on the proposed SAWDSL method is actually a mixed method. After dividing the consumption data into small and large consumers, a point demand assignment practice is used to assign the large users/demands directly to the nodes and then, through a "flow distribution technique", the remaining demand is grouped. Nevertheless, the SAWDSL lump sum areas' flow was not (mostly) GIS polygons and was undefined. Some areas may have linear spatial reference along streets (and pipes) and then proportional allocation by street reference length and, in some cases, by building density. In suburban areas with no street reference recordings, the "equal distribution technique" is preferred.

The first step to estimate the actual value of the water demand at the model's nodes, according to the SAWDSL method, is to record both the SIV and the water consumed based on the water bills referred to all water meters. Consumers are classified into major and small, depending on water-use level based on the types of water uses/users and the model's characteristics, with the former set as distinct nodes in the model. When water users of a single node belong to different groups, a further surveillance of these groups in the model is required. As big water users follow distinct nodal consumptions, SIV forms a difference consisting of the remaining revenue water and the total nonrevenue water (NRW) use that must also be distributed at the model's nodes. The water users are classified as big or small considering the water meter data and the full address details inside the water bills. It is very significant for all water meters to be supplemented with full address information through field checks and then form a complete database properly structured (e.g. in excel worksheets). Since there is a need to determine the "link" network's water meters with particular nodes of its hydraulic model, the spatial records of the water meters should be as accurate as possible. Also, the determination of the suburban area limits, the rural area limits, and the starting and ending points of each street is very crucial to divide the water meters in the three respective categories (urban; suburban; and rural). All water meters inside the urban area limits, or with street address data (with specific number or not), belong to the first category (i.e. urban). These water meters, according to their full address information, are linearly allocated along a street. Their recordings will be classified in street reference groups so that a particular number of hydraulic model's nodes will be matched to each reference route. The sum of each street reference group water meter recordings will define the total water demand of the specific route based on Eq. (1). Since it is obvious that at the street intersections, some nodes will be part of two or more reference routes, a number of hydrometers HA will correspond to the street reference A, with total consumption WDA. This WDA of the street will be modeled with NA nodes in the hydraulic model so that an equivalent length influence LA(i) will correspond at each node NA(i) of the street reference group A. This LA(i) is derived using Eq. (2), in order the sum of the equivalent length influences resulted to be equal to total street length (SLA(i) = LA). Assuming that 50% of the total length of the pipeline, connecting two successive nodes, is being supplied by each node, this distribution of the water demand at each node depends on the street length each node "supplies." The sum of the total demand placed in the street A is then allocated to the JA(i) nodes (Eq. (3)). Furthermore, the water demand allocated to a node that belongs to more than one street reference routes will be a sum of demands (Eq. (4)).

$$\mathrm{WD_A} = \mathrm{S(WMR_A)} \tag{1}$$

$$\mathrm{L_{AJ}} = \frac{\mathrm{D(N_{A(J-1)}, N_{A(J)}) + D(N_{A(J)}, N_{A(J+1)})}}{2} \tag{2}$$

$$\mathrm{WD_{AJ}} = \mathrm{WD_A} \times \left(\frac{\mathrm{L_{AJ}}}{\mathrm{L_A}}\right) \tag{3}$$

$$\mathrm{WD_J} = \mathrm{S(WD_{AiJ})} \tag{4}$$

where $\mathrm{WD_A}$ is street A total water demand based on the recordings of the water meters located in street A; $\mathrm{S(WMR_A)}$ is the sum of the recordings of the water meters located in street A; $\mathrm{WD_{AJ}}$ is the final nodal base demand of node J in street A; $\mathrm{L_{AJ}}$ is street A equivalent length supplied by the node J; $\mathrm{D(N_{A(J-1)}, N_{A(J)})}$ is the street length between the nodes $\mathrm{N_{A(J-1)}}$ and $\mathrm{N_{AJ}}$; $\mathrm{WD_J}$ is the final nodal base demand at Node J from all streets $\mathrm{A_i}$ linked to it (if Node J "belongs" to more than one streets $\mathrm{A_i}$); and $\mathrm{L_A}$ is the total length of street A.

Any water meter whose reference street is partly located within the urban area limits belong to the second category. An example of this group water meters along pipelines lying below city streets (regarded as city exits) that continue to run for kilometers beyond the urban limits. In this category, the distribution of the water demand is done in a combined manner. The perspective of equivalent street length distribution appears here, except from the nodes within the urban area, where increased equivalent street length factors are applied, depending on the increased number of the water meters or/and buildings/residences as is evident either by the full address details of the water meters. Finally, water meters which record the consumption of rural areas belong to the third category. Water meters of this category contain spatial data with domain name rather than address and the water demand of those areas is equally distributed to the number of nodes of this area.

2.1.3. Allocation in time

The process of allocating the water consumption has not only to do with space but also with time. The 24 h distribution of water use varies between working days and weekends and also amongst the working days themselves. It also follows a seasonal variation between winter and summer months. The existence of different types and kinds of water users makes the simulation of the actual water consumption at node level an even more difficult task to handle. Although it is possible to study some customers in detail, focusing on their water use habits and patterns, and extend the findings of this study to other similar users; this kind of data reduction involves certain inherent risks. Large users' consumption (e.g. industries, hospitals, hotels, etc.) as well as their daily pattern must be separately determined. The existing methods of residential consumers' demand allocation are based on typical "unit" water consumptions for different daily needs (e.g. drinking, bathing, cooking, etc.); combining the individual stochastic consumption of individual customers and reducing the sum to define the total respective water use in a wider area for a longer period.

2.1.4. Separation of the water demand in pressure-dependent and volume-dependent parts

The basic assumption, made in the model analysis of water distribution, is the conservation of mass principle at each node of the system, where "node" is the network's site from where supply is required in the form of demand. Although this supply is usually considered known and stable regardless of pressure variations, this is only applicable when pressures at all nodes are high enough for the demand to be considered pressure independent. Whenever a failure occurs, the nodal pressures are affected and some areas may not have the required pressure. When the "supplied" pressure (at node level) is low, both the nodal demand and the water available depend on that pressure. Unlike the conventional approach of demand-driven analysis, demand is a function of pressure, so-called pressure dependent demand (PDD); however, it is believed that a junction demand is not affected by pressure if the pressure is above a threshold [12]. The nodal demand is reduced when the pressure is dropping below this threshold and it is zero when the pressure becomes zero (Fig. 1). For the majority, however, of the networks is realistic to distinguish the consumption in PDD and volume dependent demand (VDD). Additionally, it is necessary to highlight that, in the software available, it is not feasible to use two separate PDD functions with different consumption rates for simultaneous application. Thus, there is a need to extract an overall percentage. The PDD rate of the total WDS's consumption will result from the average of the rates of PDD percent of water uses and

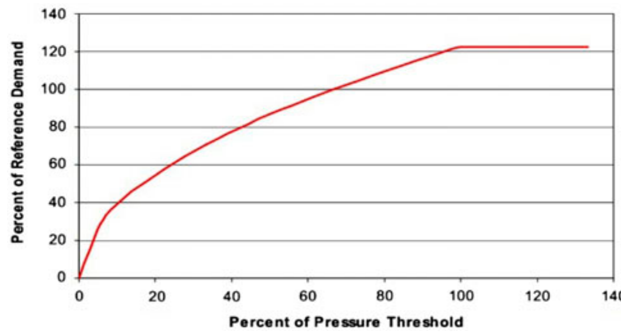

Fig. 1. A typical PDD curve [12].

of water loss (Eq. (5)). The spatial variation of the PDD rate at the model's nodes will be defined by the formation of district metered areas (DMAs) and the export of different water loss rate and hence different PDD rate.

$$PDD_{(SQ)} = [PDD_{(QWU)} \times Q_{WU} + PDD_{(QWL)} \times Q_{WL}]/SQ \quad (5)$$

As mentioned above, the separation of demand is necessary to result in a more accurate simulation closer to real conditions. VDD includes consumptions that depend on the water volume required, but not on the supplied pressure. Typical examples are water used in dishwashers, washing machines and toilets (flushing). On the contrary, PDD includes consumptions which depend on pressure, i.e. when a possible reduction in pressure occurs, reduction of consumption will follow. Typical examples of such consumptions are the use of shower, leaks, and breaks. To better model a WDS, it is necessary to separate the various consumptions in PDD and VDD ones and assess the part of the nodal demand that is pressure dependent. There are many studies worldwide that calculated the percentage of each individual use of household consumption (Figs. 2 and 3). These rates should be adapted to local conditions and if possible, the water utility should validate them via infield measurements. Then, knowing whether each use is PDD or VDD, the overall PDD rate of water use excluding water losses will be extracted. Water loss represents a much larger percentage.

2.2. Non-revenue water

2.2.1. Existing approaches

When it comes to forming the water balance of the entire network, although the preferred situation would

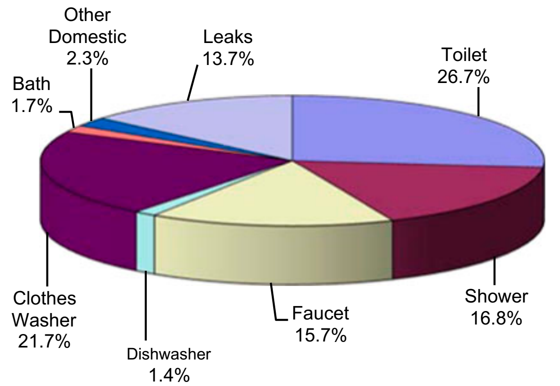

Fig. 2. Indoor per capita use percent by fixture, 12 study sites [13].

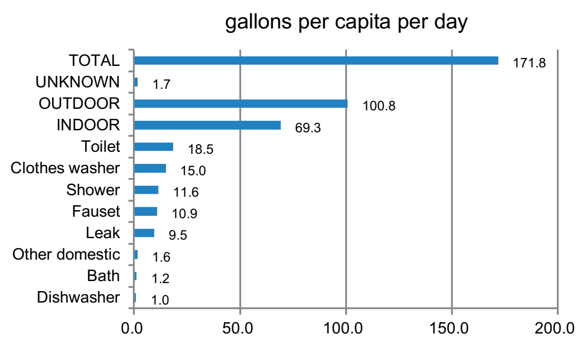

Fig. 3. Mean daily per capita use, 12 study sites [13].

be for the total metered water use of all water users to be equal to the total water volume entering the system (SIV; that should be equal to the water coming from the raw water treatment plant), the actual conditions are quite different. The "lost" water volumes, due to the authorized unmetered water use (mainly municipal) along with water losses (both real/physical and apparent/commercial ones), consist the NRW, and refer to the entire water supply chain. These water volumes owe their existence not only to water being lost due to leaks and breaks occurring in pipes but mostly to poor connections and connecting pipes serving customers. Moreover, NRW significant reasons are water metering errors and inaccuracies, illegal use (theft), and authorized unmetered water use (supplied for free). As already stated, it is crucial to split these water volumes and introduce them to the model either as a separate water use being a real competitive one to the actual water use [14], or merge them to the existing ones. Since the actual distribution of these quantities is undefined, it would be wise to equally or proportionally distribute the overall unmeasured consumption to all the nodes of the model [2]. A greater rate could be given to a specific part of the WDS being more vulnerable to suffer leaks due to the age/aging or material of its pipes. Trifunovic et al. [15] divided leakage modeling into these three possible perspectives: (a) a demand multiplier; (b) a separate demand category; and (c) use of the emitter node feature.

2.2.2. Analysis and reallocation of its parts

To better simulate the NRW, it should be further analyzed to its components. One of the best indicators of "good practice" of IWAs model is the volume of NRW as a percentage of the SIV [16]. The NRW volume represents the volume of water as a part of the SIV, which does not generate revenues. But it does not take into account the different values of the NRW components or the cost of the system [17]. The calculation of each of the three main NRW components (unbilled authorized consumption, apparent losses, and real losses) is the first step of the process. Unbilled authorized consumption includes fire fighting, cleaning of mains/sewers, irrigation of municipal gardens storage tanks cleaning, water used for roads cleaning, etc. It might be measured or not, according to the practices applied by the local water utility. Apparent losses consist of unauthorized consumption (theft or illegal use) and water meter errors (regarding its readings or data handling). The calculation of these volumes is based on structured sampling tests, defined through a process followed by the water utility. Real losses represent water volumes lost due to all types of leaks, breaks, and overflows of the mains, tanks and customers' connections, and service pipes, up to the point of the water meter. Each of these NRW parts should be separately simulated. Apparent losses should be proportionately aggregated to the nodal base demand, as it takes place in a similar manner across the entire network. Real losses should be allocated as a distinct consumption with its own 24-h demand pattern within each DMA. In each DMA, data such as pipes' installation year, average pressure, and density of connections should be recorded and form specific weighted factors, that will then be applied to the SIV of each DMA. As for the unbilled authorized consumption, its simulation will depend on the quality of its related spatial data and the water utility's policy. If the spatial data is digitized in a GIS (e.g. parks, squares, public buildings, etc.), then these water demand will be placed separately at specific nodes, which would meet the criteria to be set. For the public sector buildings, time distribution will be identical to the variation of commercial buildings' demand. In addition, other water uses (e.g. watering public gardens) will have an original pattern of time distribution.

2.2.3. Time pattern of real losses

When modeling a WDS, the diurnal demand pattern should be defined, there are several studies available in the literature regarding measurements of residential, commercial, and industrial consumption which can help the modeler, although each network is unique and must be treated as such (field measurements). The actual variance of consumption can, therefore, be recorded in a 24-h basis at pilot consumers and, then, be extended to the rest of the model. NRW represents a very large percentage of the SIV since it may be more than 50% of it. Although it is well known that leakage increases as the water demand decreases leading to increased operating pressures [18–22], to form the losses' daily pattern, is more than a difficult goal to accomplish. The type of soil and the kind of leakage determine the flow rate through a leak. The OS number can be used to show which of the two elements is dominant for varying leakage flow in time. For existing water systems, the OS number can be specified for a range of leaks. Since the term "typical" leak does not really exist, a large variety of values for the parameters of Eq. (6) was examined to specify the OS number, revealing that OS is remarkably greater than 1, proving that in most actual leakages, the orifice head loss equation prevails [23]. A flow due to a leak can usually be modeled using the orifice Eq. (7), when the OS number is large. In this equation, C_d is the discharge coefficient, A_0 is the area of orifice (m^2), g is the gravitational acceleration (m/s^2), and h_0 is the head loss through orifice (m). To design a typical water distribution model, Eq. (7) is transformed into Eq. (8), where most of the parameters are contained into an emitter coefficient K (P is the inner pressure (Nt/m^2).

$$\mathrm{OS} = \left(\frac{\mathrm{KAQ}}{2gL}\right) \times \left[\frac{1}{(C_d \times A_0)}\right]^2 = \frac{h_0}{h_s} \tag{6}$$

$$Q = C_d \times A_0 \times (2gh_0)^{0.5} \tag{7}$$

$$Q = K \times P^{0.5} \tag{8}$$

The calculation of the water losses diurnal pattern could be done through the diurnal pattern of leaks, which depends on pressure (Eq. (8)). Considering the spatial and temporal variation of pressures, the average values of pressures per hour in each DMA must be calculated first. Then, the diurnal pattern of each DMAs real losses will be calculated via Eq. (8).

Alternatively, to determine the diurnal pattern of the WDS's overall leakage and be closer to the existing conditions at the same time, the WDS must be divided into DMAs. At each DMAs (unique) entrance, the amount of the incoming water Q_{tot} can be safely measured and the diurnal pattern $T_{(i)tot}$ can be recorded. The resulting figure expresses the total consumption of all users for each DMA, consisting of residential, commercial, industrial, municipal, and water losses. Commercial, residential, and industrial uses' diurnal patterns ($T_{(i)tot}$) are pilot recorded and an average of the recordings is calculated at the DMA level. The volume of water loss Q_{WL} can be estimated through the water balance formed for each DMA. Thus, in Eq. (9) the diurnal variation of water losses $T_{(i)WL}$ (hourly step i), is the only unknown parameter. The final diurnal pattern of WL ($T_{(i)WL}$) could well be the average of the results of the two computational methods.

$$Q_{tot} \times T_{(i)tot} = Q_{WU} \times T_{(i)WU} + Q_{WL} \times T_{(i)WL} \tag{9}$$

3. Simulation of Kos Town WDS

3.1. Basic data of Kos Town WDS

Kos Town, the birth place of Hippocrates, father of the modern medicine, is the capital of Kos Island situated in the south-eastern part of Greece, in the Aegean Sea. Kos Town population exceeds 20,000 people (2001 census). Kos Island is a famous tourists' destination (ranked 4th in Greece). Thus, the population during summer time exceeds 50,000 people. DEYAK is the local (municipal/public) water utility. Kos Town WDS is widely spread covering a huge area. It also supplies water to more than 100 major touristic resorts, each having daily water needs of (more or less) 200 m^3. The total daily water volume supplied by the WDS reaches its peak (12,579 m^3) during summer, while during winter is limited to less than half (5,927 m^3). Several of the touristic resorts (fully or partially) cover their own summer water needs using their licensed private wells. Private water use is registered through 13,000 water meters. There are three pressure zones formed in Kos Town: (a) a limited higher zone; (b) a medium zone at the south (altitude ranging from +30 to +50); and (c) a low zone (covering 95% of the total water demand); (Fig. 4).

3.2. SAWDSL implementation in Kos Town WDS case

After the digitization of Kos Town WDS, the demand allocation followed. DEYAK provided data

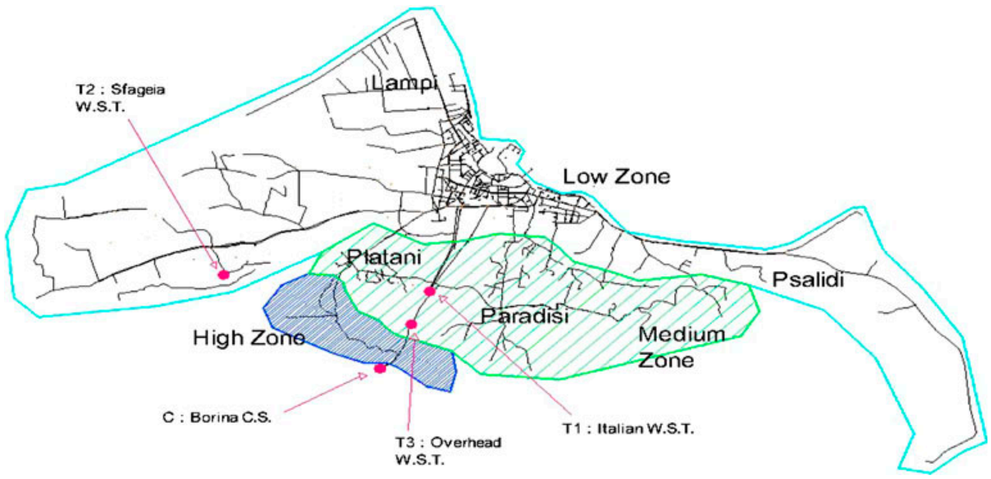

Fig. 4. Pressure zones, water storage tanks in Kos Town water network.

regarding all water meters' readings (data of 2008). Each hotel water meter registry over 400 m^3 per 2 months (billing period in Kos Town) was separately validated, through 10 d of continuous recording (in field measurements). The 12,465 water meters in place were classified into 184 groups according to their geographical reference (street or suburban area) apart from big hotels' water consumptions which were separately allocated to specific nodes. All 184 groups of water meters were introduced into MS Excel®, further processed, modified and merged where possible, to reduce their total number to 155, in order to "link" the 644 nodes of the model. There were three categories of water meters' groups: (a) streets (within the limits of Kos Town development plan), which were the majority (124 groups); (b) areas outside this plan, where water meters had been georeferenced to a specific region (22 groups); and (c) streets which were partly laying within the urban tissue (with a high population density) and partially outside it (with a quite lower population density) (nine groups). According to the assumption of the equivalent street length (i.e. each node "received" the proportion of the street's overall water demand based on the ratio of length corresponded to its total length), the first category was spatially allocated. The division of the area's total water demand based on the number of its nodes led to the allocation of the second category. The demand allocation of the third category was a mixture of the above described ways. It followed the same allocation of the equivalent road length, apart from nodes within the limits of the urban tissue, where correction factors were used due to the different population densities met across the street. The 107 big customers found were appropriately distributed either at the model's existing (63) nodes or new (pseudo) ones (44). The number of customers (water meters) is bigger than the total number of the new nodes. That happens as some hotel units are served by more than one water meter. Also, some units inside the urban limits were appointed to existing demand nodes. So, a combined, functional and dynamic distribution tool was created using MS Excel®. Through this procedure, each node automatically gets its consumption by any street or area it is linked to. It should be mentioned that there were cases where the overall water consumption appointed to a node was considered to be the sum of the resulting consumption of up to six subgroups of water meters. The NRW volume was modeled as a distinct water use, distributed appropriately to each existing node, without creating new ones, according to the base demand's percentage of each node which results from the SAWDSL method.

3.3. Allocation in time

One of the characteristics of Kos Town is the large deviations regarding the population being served. Since winter and summer consumption levels vary a lot, the WDS was resolved separately in a bimonthly basis following the billing period the water utility applies. As already mentioned, the two classifications of the water users were: those using more than 400 m^3 in a bimonthly basis (hotels) and the rest. By hourly recording the data of a sample of water meters of both categories to achieve maximum accuracy, through a pilot project, the daily water demand patterns were formed for each category and then introduced to the data resolution.

3.4. NRW in Kos Town WDS

3.4.1. Separation of water consumptions in PDD and VDD

Fig. 5 presents the main components of the residential water use in Greece [24]. They are pretty similar to the findings of the international literature (Fig. 2). In Kos case, the daily residential water use was divided into three types: personal hygiene (i.e. shower, bath, and washing hands), toilets, and other uses representing 36, 27, and 37% of the total consumption, respectively. Then, for each of these subuses the PDD and/or VDD parts were identified (Table 1), resulting to the respective portions regarding the total residential water including both the authorized and the unauthorised use (Fig. 6). Regarding the water losses' nature (35% of the SIV), studying their components, it was assumed that the majority is classified as almost fully pressure dependent (Fig. 7). Finally, the PDD rate of total consumption resulted to be 70.5%.

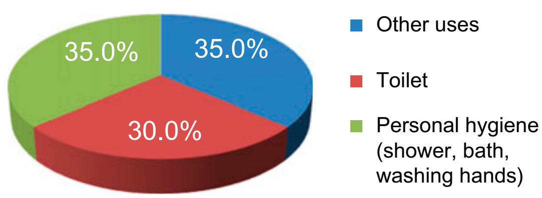

Fig. 5. Residential water use typical allocation in Greece [24].

Table 1
Classification of water use in PDD and VDD

Residential water uses in Kos	(%)	Classification
Personal hygiene (bath, shower)	36.0	PDD
Toilet	27.0	VDD
Clothes washer, dishwasher	18.0	PDD/VDD
Potable water	4.0	VDD
Garden, car washing, other uses	15.0	PDD

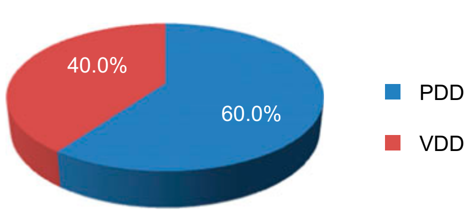

Fig. 6. Separation of water use (water losses excluded) in PDD and VDD.

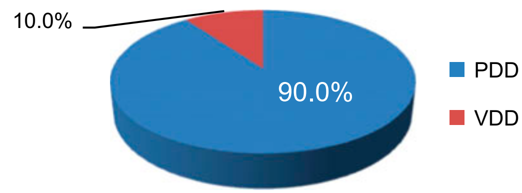

Fig. 7. Separation of water losses in PDD and VDD.

3.4.2. Diurnal pattern of real losses in Kos Town WDS

During the development of Kos Town WDN model, both approaches to calculate the 24-h variation were applied. According to the first approach, since the network was not divided into DMAs, the 24-h variation coefficients that apply to the entire network were exported. The pressure daily fluctuations were measured at selected points, which comply with the mean pressure derived from the calibrated model, and then, using Eq. (8), the coefficients of the 24-h variation were exported (Fig. 8). According to the second

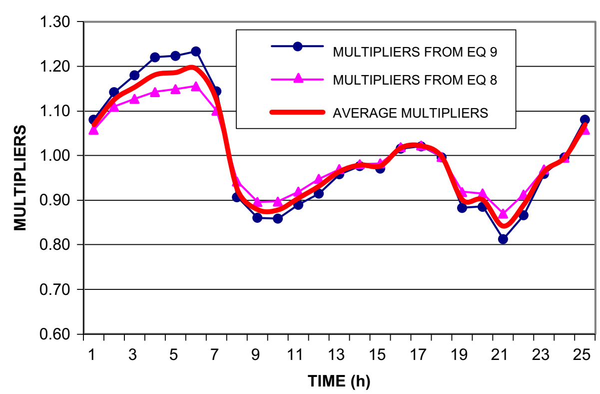

Fig. 8. Real losses daily pattern resulting from Eqs. (8) and (9).

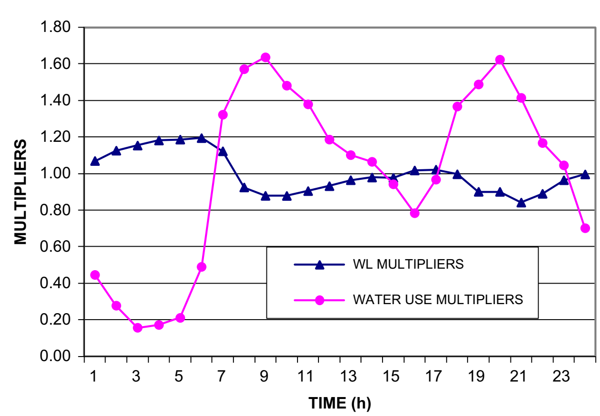

Fig. 9. Real losses and the rest water consumption daily patterns applied to the model.

approach, recording the daily patterns of the incoming water and the residential use, along with their volumes, while assessing Kos Town WDN water balance components' volumes, the daily pattern of real losses was finally exported using Eq. (9) (Fig. 8). Then, the average of the two solutions was calculated and applied to the model (Fig. 8). Fig. 9 presents, both the variance of losses and daily fluctuation of water use, as resulted after field measurements in representative consumers.

4. Comparing the results

4.1. Calibration and verification of the model

After the model was developed, its calibration and verification followed. The modeling software used was Bentley's WaterGEMS. During August, pressure was ceaselessly recorded in 13 points of the network. Since there was no SCADA installed, data was recorded using an accurate portable pressure meter. The Darwin Calibrator (DC) module for manual calibration was used. To adjust the recordings, a roughness classification of the nodes was done, depending on their material and age, utilizing recorded field data collected for the calibration study, introduced to the DC module. The minimization of sum of squares between recorded data and model resulting values was used as a factor to define categories. The maximum deviation threshold set was 10%. To verify the model, different data-sets from those used during the calibration, were selected.

4.2. Comparing demand allocation and pressure results

To check the new method on the spatial distribution of registered water consumptions, field data was collected and compared with what the water utility was using (Thiessen polygons method or Voronoi diagrams). The role of Thiessen polygons is multidimensional. They are used as models for spatial procedures, as nonparametric techniques in point pattern analysis, as organizing structures for displaying spatial information, and for estimating individual probabilities in point patterns [25]. The MW-Voronoi diagram considers both the location and the weighted factor of each polygon, in contrast to the typical Voronoi method, where the only factor is the location [26]. The factors that multiply the Voronoi diagrams have many different characteristics which influence the prices of the magnitude that have been expressed through this process. The weighted factors are determined by the existing data and sensitivity analysis and ought to be implemented to the typical Voronoi diagrams. This process is widely used by hydraulics software (e.g. WaterGEMS) for demand distribution when adequate information is lacking, and multiplies the original polygons, using population or land use coefficients. Applying the MW-Voronoi diagrams process, the nodes used in dividing the area of Kos Town served by the WDS are determined. There were 610 nodes out of the 644 initially defined, forming, thus 610 polygons, covering a total area of 12,873,447 m^2 measured using AutoCAD since hotels nodes and nodes located above the water mains were not included, as the ultimate goal was to spatially distribute only the domestic water use. To result to a better perspective of the actual circumstances, since these polygons do not reflect areas of equal water demand, weighted factors must be assigned to each polygon, depending on several features of the area involved (e.g. land use, building density, building height, etc.). Based on domestic demand, two factors were chosen for their linear nature among the candidate factors tested (through the existing data). The first factor refers to the residential coverage of each polygon, calculated with absolute accuracy between 0.00 and 1.00. Using AutoCAD software, building area polygons were created inside the existing Thiessen polygons, and thus the covered surface of each Thiessen polygon was digitized and measured. The second factor, which refers to the height of the buildings, takes the value 0.50 for suburbs and areas around the city and 1.00 at the center of the town. In the rural and areas outside the town limits, the allowed buildings' height is 7.5 m, while in the town center, is 15 m. These two factors consist a unified "buildings volume" factor, which is linearly related to the population density. Compared to existing data, this process appeared to be the most appropriate to result to an initial comparable scenario to the SAWDSLs method. To compare both methods, the water demand appointed to each node expressed as percentage of the WDSs total water demand was used.

In order to reach to safe conclusions, cases from all three categories of water meters' groups were checked. M. Nathanael street starts from the town center up to the suburban area. As we are heading away from the town center, the density of the buildings rapidly decreases. The water demands (resulting from the SAWDSL method) appointed to each node result in higher pressure values at the town's centre, while as we move to the suburbs, the Voronoi method gives higher pressure values (Fig. 10). Kanari Street (Fig. 11(a)) is in the town center. Also, in that case, the Thiessen method compared with the SAWDSL one underestimates the nodal pressures. The SAWDSL method succeeds to highlight these water

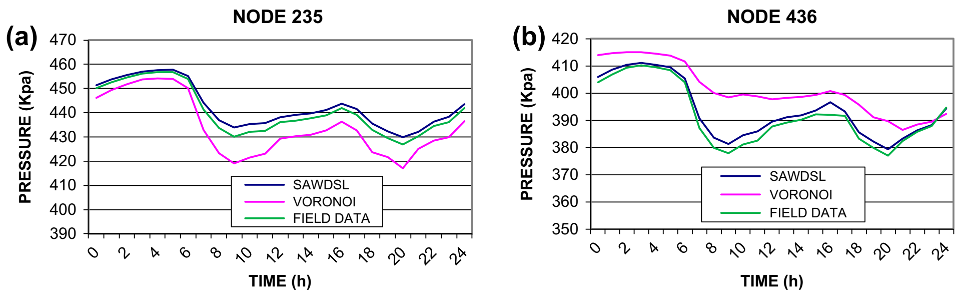

Fig. 10. Observed and simulated pressures in both SAWDSL and Voronoi methods (a) in node 235 (downtown) at M. Nathanael str.; and (b) in node 436 (suburbs) at M. Nathanael str.

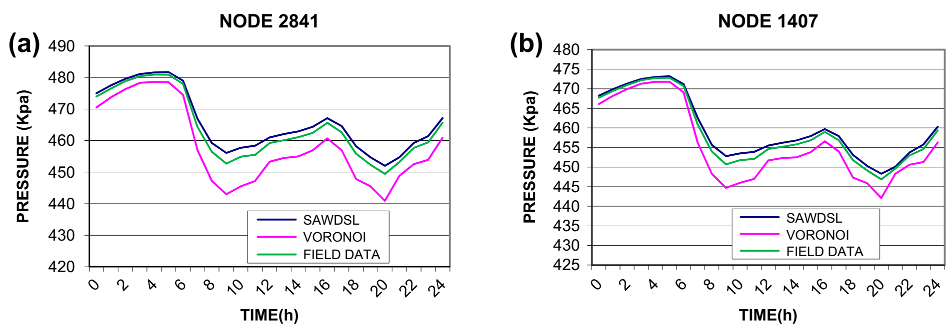

Fig. 11. Observed vs. simulated pressure values in both SAWDSL and Voronoi methods (a) in node 2841 at M. Kanari str.; and (b) in node 235 at M. Psaron str.

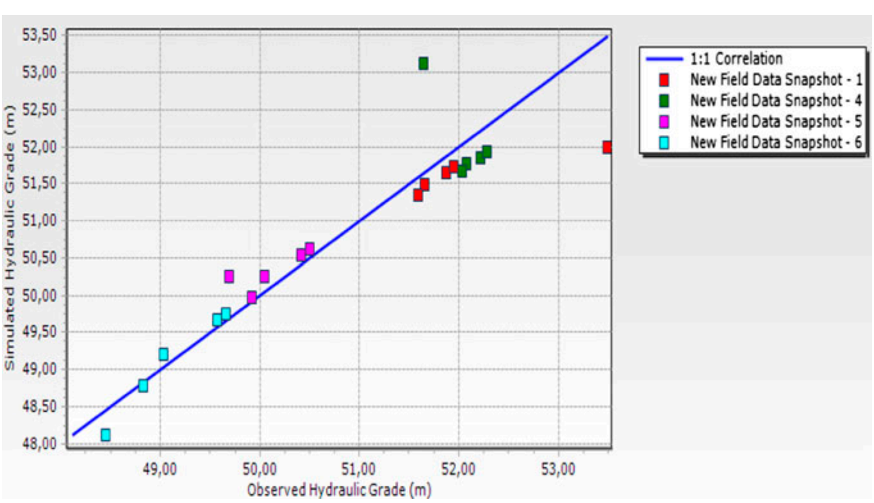

Fig. 12. Correlation between observed and simulated HG in SAWDSL method.

consumption behaviors, while the Thiessen method based on population densities highly underestimates them. Psaron Street (Fig. 11(b)) is in the town center near the beach. Like in Kanari Street, the Voronoi method leads to relatively higher rates of consumption than the first method does, resulting to lower pressures than the field data.

The general conclusions can be summed up to the following: (a) SAWDSL method results in smaller water demand values at nodes located inside the town

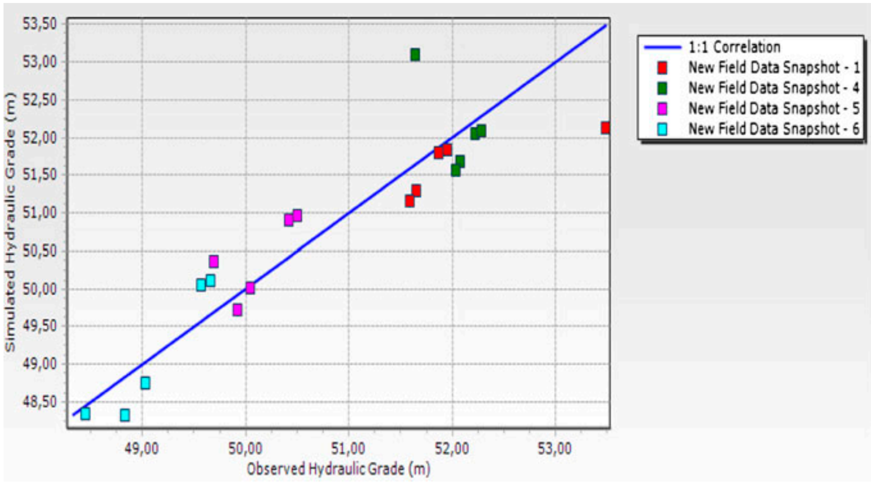

Fig. 13. Correlation between observed and simulated HG in Voronoi method.

limits compared with Thiessen method. The differences are smaller than 2%; and (b) on the contrary, the demand appointed to the suburban nodes is underestimated, when the Voronoi method is used. SAWDSL method results are mainly 10–30% higher compared to the Voronoi method, regarding many of suburban nodes (a few dozen) (Fig. 12).

4.3. Comparing pipe roughness results

During August, where demand reaches its peak level (the best time for the model calibration), pressure was continuously recorded in 13 points of the network, using a precise portable pressure meter, since there was no SCADA installed. During the calibration process, the pipes were grouped by material. Using the Bentley Watergem's DC, the internal roughness groups were modified keeping the nodal consumption fixed. Figs. 13 and 14 present the correlation between observed and simulated hydraulic grade of SAWDSL and Voronoi methods, respectively. SAWDSL method resulted to a more accurate approximation of the actual water use allocation at nodes level, minimizing the need to modify the values of pipes' roughness coefficients, to bridge the gap between model outputs and field data. Reliable estimations of pipes' roughness values leads to safer assess pipes' aging factors, and thus their carrying capacities [27]. Fig. 14 presents the values of *C* coefficient from the calibration of the model using both methods.

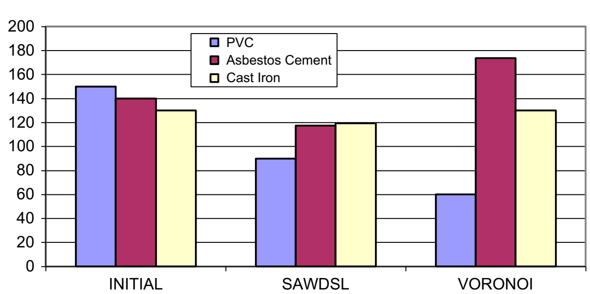

Fig. 14. Initial and modified (through model calibration) values of Haazen Williams C factor of the main three WDN's materials.

5. Concluding remarks

In this paper, some crucial aspects regarding the development of the hydraulic simulation model of a WDS are analyzed. It is a fact that when a water utility is not very advanced, it takes greater effort to get valid results. Furthermore, it is crucial to achieve reliable outcome through a procedure which will neither be time-consuming nor expensive. A precise view of the network is the main priority. In order to come up with the best results, and in time, with the minimum possible cost, it is of rather paramount importance to appropriately spatially allocate the water demand at the model's nodes. In Kos Town case, since the necessary data and money were not available, a new method (SAWDSL) that allocates the water demand at street level was preferred. Its outcome was compared with that of the Voronoi diagrams method and to field measurements. One of the conclusions pointed the excessive emphasis given at the urban areas, when the Voronoi method is used, in contrast to the nonurban areas. The calibration process showed that there were significant differences in the recorded pressures. To reduce the difference between the model of the Voronoi method and the existing condition, other specific factors (e.g. residence type, education level, etc.) should also be taken into account while developing the weighted factors used. Base demand allocation in WDS models, whatever the process used for measurement, is always referred at the model nodes as nodal demand. Base demand for each node's "area of influence" is measured as a percentage of total demand when using the Voronoi diagrams method. SAWDSL places nodal base demand as the proportion of the street's overall water demand according to the ratio of length corresponded to its total length, after having classified the water bills. Most of these categories of water bills have linear street georeference and the minority has spatial georeference. Using the SAWDSL method, the outcome adequately approached the real operating conditions. This new process is suitable for networks that do not have GIS records for water meters, but there is a recorded street or suburban area reference, which is a very common situation among developing countries. The importance to determine the PDD and VDD parts of each water demand is also presented. Its usefulness during the modeling process has mainly to do with efforts to reduce water loss through pressure management practices. The proper approach of this percentage indicates a proper simulation of actions, some of which will then be applied to the field, following a decision of the water utility manager. Similarly important is the determination of water losses diurnal pattern. Here, two suggested calculation methods used were presented.

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