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Assessing the results of a virtual pressure management project applied in Kos Town water distribution network

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ABSTRACT

Water pressure management (PM) is one of the most cost-effective ways for a water utility to reduce water leakage, pipes' bursts, improve the level of services provided to its customers and lower its operating expenses. The present paper presents a pilot pressure management project designed for the water distribution system of Kos Town (capital of Kos Island, Greece). Kos Town experiences extreme variations regarding its population served by the local water utility between summer and winter. The PM implementation was achieved by developing the system's hydraulic simulation model using the commercial software, Watergems V8i. For the water demand allocation of the model, the spatial allocation of water demand at street level approach was used because the customers' water meters were not geo-referenced. The results were compared to multiplicatively weighted Voronoi diagram method's results and to field measurements. The simulation process took 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 used was divided into a pressure dependent part and a volume depended one. Both parts were introduced to the model. The designing phase of the PM included the formation of district metered areas and Pressure Reducing Valves (PRVs) installation. The reduction in pressure within acceptable regulation limits resulted in the reduced needs of System Input Volume (SIV), due to significant reduction of anticipated water losses and authorized consumption, as both these "water uses" are pressure dependent. There were many simulations of different scenarios in time (monthly) and PRVs' configuration. Regarding the latter, several types of PRVs and their settings were tested (e.g. fixed PRVs; PRVs with modified daily pattern; PRVs combined with local pressure boosters). The virtual scenarios resulted in reducing the SIV up to 24%. The related water savings have a direct positive environmental impact on the aquifer supplying Kos Town. These outcomes persuaded the local water utility to proceed with the actual implementation of the pilot study by installing the necessary system devices (either for measuring data or for pressure reducing) in more than 40 manholes across the town.

Keywords: Water losses; Pressure management; DMAs; PRVs

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1. Introduction

In the last decades, several local water utilities identified that reduction of excess pressure could significantly reduce the number of leaks and burst occurrences, and they began to practice and promote active pressure management. It is now widely known that pressure management in combination with district metered areas (DMAs) implementation is a strong leakage management tool [1–3]. A lot of water utilities have reported water distribution system (WDS)'s pressure reduction and thus, leakage reduction [4–7]. Water utilities that have recently followed the pressure management policy are now finding that, there are more advantages than reduced leak flow rates and burst repair costs, such as demand and asset management. On the other hand, there are still local water utilities that have not yet followed the same path, perhaps because they fear to lose any revenue related to reduced pressure provided to the customers' water meters, or uncertainty of the predicted/expected benefits that might not justify the necessary investments' costs. However, during the last years, the effect of pressure management on burst frequencies of mains and service connections has also become more widely known. In systems with continuous supply, rapid reduction in bursts and repair costs are now changing the economics of pressure management and the perception that leaks and bursts can only be managed by repairs or pipe replacement. Utilities that have recently implemented pressure management schemes are now realizing that reduced leak flow rates and burst repair costs are not the only benefits. There are several recent studies that estimate the benefits of pressure management both in breaks [8] and real losses [9,10] reduction. Pressure management is a brilliant tool not only for leakage control, but also for demand management, water conservation and asset management. A better pressure management implementation requires network's break down to smaller segments (DMAs) for easier management and inspection. In each section, usually a pressure control device is installed to achieve the goal of reducing Non-Revenue Water (NRW). To efficiently achieve the above goals, the optimal separation of the network into DMAs, as well as the optimal pressure reducing valve (PRV) location in each DMAare both required. The pursuit of both tasks can be accomplished by testing scenarios developed in a calibrated and validated simulation model of the network. DMAs formating is a multi-dimensional problem and there have been many efforts to be solved using optimization techniques [11,12]. There were used algorithms such as, "Breadth-first search", "Deapth-first search", [12–15] and "Multi-agent systems" [16–18].

To study the PM application, the hydraulic model of Kos WDS was developed. Existing water distribution modeling applications use the spatial analysis capabilities of GIS software and data bases, such as geo-coded records of water meters. But this cannot be done because the water meters of Kos WDS were not geo-referenced. Another important aspect of demand allocation is NRW "demand" allocation, since it is a large part of system input volume (SIV) in developing countries. After the development of the basic hydraulic simulation model, its calibration took place by measuring pressure and flow rates at critical nodes [19]. The discrepancy between field measurements and model calculations is mitigated by modifying the values of the pipes' internal roughness coefficients [20]. This study uses the spatial demand allocation based on a spatial allocation of water demand at street level (SAWDSL) [21] method. This method divides the consumption data into small and large consumers and a point demand assignment practice is used to assign the large users/demands directly to the nodes. Then, through a "flow distribution technique" (which will be presented briefly in the next chapter), the remaining demand is grouped and allocated to the nodes. The strategy of flow distribution consists of distributing lump-sum area water use data among a number of service areas and, further, their associated demand nodes. The distribution of the total water use among the individual nodes of the "lump-sum" areas of SAWDSL method was impossible to be defined in a uniform way [21]. Some areas had linear spatial reference along streets and then proportional allocation by street reference lengths and, in some cases, by building density. In suburban areas with no street reference recordings, the "equal distribution technique" was preferred.

Additionally, this study deals with the implementation of a "virtual" project including the formation of DMAs and installation of PRVs in the simulated model of Kos Town WDS. The reduction in pressure within acceptable regulation limits, resulted in reduced SIV. This was provided by the pressure dependent demand (PDD) function of the WaterGEMS software. Daily operating scenarios using fixed PRVs, PRVs with modified 24-houred pattern and combinations of PRV types with the application of local pumps were checked. The scenarios resulted in reduced SIV levels (12.22–24.15%). These results persuaded Kos water utility to install the necessary devices to actually implement the "virtual" project. The conclusions led to indisputable decisions on the acquisition and application of the suitable equipment.

2. Implementation

2.1. Basic data of Kos town WDS and its hydraulic model

The island of Kos is situated in the south-eastern part of Greece, in Aegean Sea and is renowned as the birth place of Hippocrates, the father of the modern medicine. The population of its capital, Kos Town, exceeds 20,000 people according to the 2011 census. Since, it is a famous tourists' destination (ranked 4th in Greece), the population during summer time exceeds 60,000 people. DEYAK is the local (municipal/public) water utility. Kos Town WDS is widely spread covering a huge area (Fig. 1). It covers the entire town and its expansions (southwest to Lampi and northeast to Psalidi settlements). The WDS supplies an extensive low-lying area (altitude: 0–30 m) and a higher one to the South (altitude: 25–50 m). There are three pressure zones formed in Kos Town WDS: (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. 1). Kos town was originally a coherent urban area developed according to a solid urban plan ever since the Italian occupation. The town, back then, was served by a well-designed water supply network. After the World War II, tourism and general development of Kos Island led to an extended urbanization, with no provision to construct/expand the necessary water services' infrastructure. The new areas extending the town limits were served by the ad hoc construction of radial type antennas, which had as a starting point the original core of the existing WDS. The total daily water volume (SIV) supplied by the WDS reaches its peak (12,579 m^3) during summer, while is limited to less than half (5,927 m^3) during winter. (Fig. 2) presents the total water volumes extracted, consumed and billed in Kos case from 1999 to 2007 [22]. Water reaches DEYAK customers through 12,465 water meters. Several of the

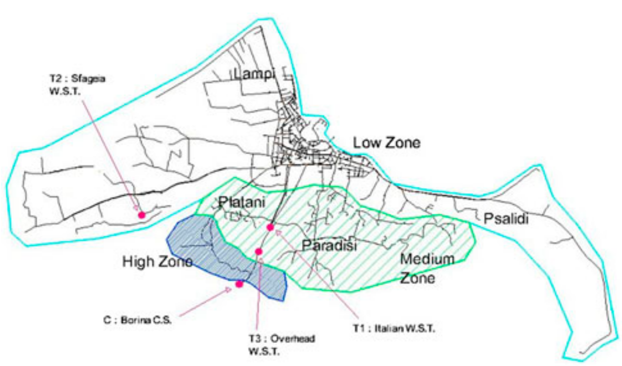

Fig. 1. Kos town WDS pressure zones and water tanks.

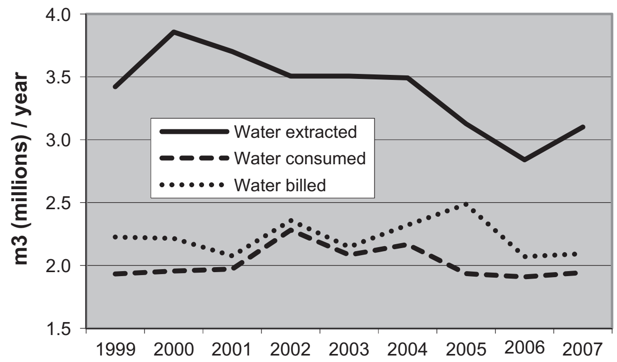

Fig. 2. Water extracted, consumed, and billed in Kos town WDS [22].

touristic resorts (fully/partially) cover their own summer water needs using their own private wells.

The hydraulic model consists of 122.64 km pipes and water mains, 694 nodes, 3 tanks and a charging shaft (Fig. 1). After the development of the model, it was calibrated and verified. The modelling software used was Bentley's WaterGEMS. During August, when demand reaches its peak level (best time for calibration) pressure was recorded (every 2 h) in 13 points of the network. Since there was no SCADA installed, data were recorded using an accurate portable pressure meter. During calibration process, the pipes were grouped by material. Using the Bentley Watergem's Darwin calibrator, the internal roughness groups were modified keeping the nodal consumption fixed.

Six scenarios regarding the six different billing periods were initially developed, which finally became 12 after using monthly step.

2.2. Water demand allocation

The spatial demand allocation based on the SAWDSL method is actually a mixed method. The consumption data are divided 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. 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 water meters, according to their full address information, are linearly allocated along a street. Their recordings are classified in street reference groups so that each reference route includes a particular number of nodes. The sum of each street reference group water meter recordings equals the total water demand of the specific route $WD_{(s)}$ based on Eq. (1). Assuming that 50% of the total length of the pipeline, connecting two successive nodes, is being supplied by each node, the distribution of the water demand at each node depends on the street length of each node "supplies". This equivalent length $L_{j(s)}$ is derived using Eq. (2), in order, the sum of the equivalent length influences resulted to be equal to total street length (Eq. (3)). The sum of the total demand of street (s) is then allocated to the j node according to Eq. (4). At the street intersections, some nodes are part of two or more reference routes. The water demand allocated to a node which belongs to more than one street reference routes will be the sum of demands according to Eq. (5).

$$WD_{(s)} = \sum WMR_{(s)} \tag{1}$$

$$L_{j(s)} = \frac{D_{(j-1),j} + D_{j,(j+1)}}{2} \tag{2}$$

$$L_{(s)} = \sum L_{j(s)} \tag{3}$$

$$WD_{j(s)} = WD_{(s)} * \left[\frac{L_{j(s)}}{L_{(s)}}\right] \tag{4}$$

$$WD_j = \sum WD_{j(s)} \tag{5}$$

where $WD_{(s)}$ is total water demand of the specific route (street), $WMR_{(s)}$ are the water meter recordings located in street s, $L_{j(s)}$ equivalent length of node j located in street s, D is the street length between 2 nodes, $L_{(s)}$ is the total length of street s, $WD_{j(s)}$ is the final nodal base demand of node j in street s and WD_j is the final nodal base demand at node j from all streets linked to it.

DEYAK provided data regarding all water meters' readings. The 12,465 water meters were classified into 184 groups according to their geographical reference (street or suburban area), apart from big hotels' water consumptions (over 400 m^3 per billing period) which were separately allocated to specific nodes [21]. 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 [21]. 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 geo-referenced to a specific region (22 groups); and (c) streets which were partly layed within the urban area (with a high population density) and partially outside it (with a quite lower population density) (nine groups) [21]. The first category was spatially allocated, according to the assumption of the equivalent street length. The division of the area's total water demand based on the number of its nodes led to the allocation of the second category, while the third category's demand allocation was a mixture of the above described ways. Through this procedure, each node's consumption was automatically calculated.

NRW (including water losses) is introduced at the nodes as separate water consumption, following the allocation of recorded consumption in combination with gravitational coefficients regarding developed maximum pressures and breaks frequency per km length of pipes for each material. The breaks frequency also considers the pipelines' age. The final coefficient of the overall "NRW consumption" which was allocated to each node j was derived from Eq. (6).

$$a_{f(j)} = \frac{a_{SAWDSL(j)} * a_{P(j)} * a_{B(j)}}{\sum_{j=1}^{n} a_{SAWDSL(j)} * a_{P(j)} * a_{B(j)}} \tag{6}$$

where $a_{f(j)}$ is the final coefficient of the overall "NRW consumption" which was allocated to each node j [%], $a_{SAWDSL(j)}$ is the coefficient of metered consumption resulting from SAWDSL method for node j [%], $a_{P(j)}$ and $a_{B(j)}$are dimensionless coefficients which reflect pressure and pipes' status influences, respectively, in "NRW consumption" of node j.

Coefficients $a_{P(j)}$ και $a_{B(j)}$ are derived from Eqs. (7) and (8). The first one expresses the influence of pressure in NRW volume which is "consumed" by node j and is equal to the ratio of the node's maximum press ure and the maximum pressure observed on the network. Coefficient $a_{B(j)}$ expresses the influence of pipes' (which are linked to node j) material and age through material's bursts rate.

$$a_{P(j)} = \left[\frac{P_{\max(j)}}{P_{\max(WDS)}}\right]^{0.5} \tag{7}$$

where $P_{\max(j)}$ is node's j maximum pressure in a random day [kPa] and $P_{\max(WDS)}$ is the maximum pressure that occurs across the network during the same day [kPa].

$$a_{B(j)} = \frac{\sum_1^k m_{s(j)}}{k} \tag{8}$$

where $m_{s(j)}$ is the bursts rate of the material's pipe of street s (as a percentage of all WDS's bursts) which is linked to node j [%], and k is the number of pipes which are linked to node j.

2.3. Forming the DMAs for Kos Town WDS

DMAs formation follows certain principles. Initially, the network's nodal pressures are developed, as well as the fire flow requirements are considered. In Greece, there are no specific standards for fire flow requirements (as in USA), but a criterion for the diameter of the inlet pipe in each DMA was introduced. This pipe's diameter had to be larger than the biggest fire fighting pipe diameter of Kos WDS which equals 150 mm. Kos network is radial. Water supply pipes are heading down from the water storage tanks into the city and then branch into smaller distribution pipes. The downtown, having the densest network, has no altitude differences since it is close to the sea. Kos Town centre was divided into 5 DMAs based on the plan view of the network so that none of the DMAs formed exceeds the limit of 1,500 water meters served (Fig. 3). As the rest of the network had large dispersion and low consumption, it was not suitable for pressure management. The main elements taken into account for the design were nodal pressure variation, fire flow requirements, water mains, population density, various specificities of the terrain (e.g. roads, parks), and the least possible number of isolation valves. Table 1 presents the basic data for each DMA formed.

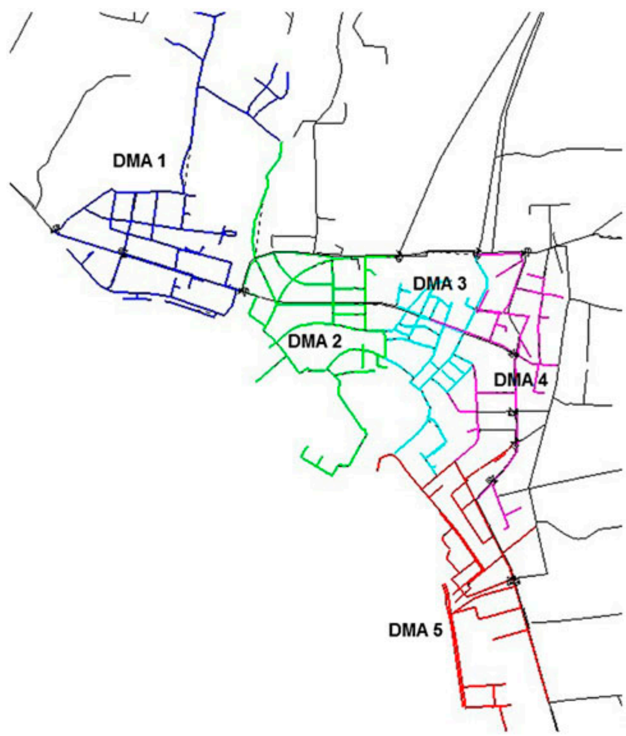

Fig. 3. The five formed DMAs of the network and the installed PRVs.

2.4. Separation of consumption in PDD and volume dependent demand (VDD)

The conventional approach is a demand-driven analysis but water demand is a function of pressure, so-called PDD and it is believed that a node demand is not affected by pressure if the pressure is above a threshold [23]. PDD can be defined as a pressure-demand relationship in a power function form [23] (Eq. (9)). By the time pressure becomes greater than the threshold value, demand stops to increase and remains constant.

$$\frac{Q_i^s}{Q_{ri}} = \begin{cases} 0, & H_i \le 0 \\ \left[\frac{H_i}{H_{ri}}\right]^a, & 0 \le H_i \le H_t \\ \left[\frac{H_t}{H_{ri}}\right]^a, & H_i \ge H_t \end{cases} \tag{9}$$

Table 1
DMAs' basic data

	Number of Water Meters	Number of Nodes	Number of Pipes	Pipes' Length (m)	Minimum Elevation (m)	Mean Elevation (m)	Maximum Elevation (m)
DMA 1a	1,087	45	51	4,609	3.0	7.3	17.0
DMA 1b	816	34	31	2,151	2.0	3.0	5.0
DMA 2	1,264	53	60	5,914	2.0	4.1	11.0
DMA 3	1,467	52	58	4,052	2.0	4.4	8.0
DMA 4	1,474	48	57	4,518	2.0	5.4	10.5
DMA 5	1,486	59	50	5,581	1.5	2.3	4.0

where H_i represents the calculated pressure at node i; Q_{ri} denotes the requested demand or reference demand at node i; Q_i^s is the calculated demand at node i; H_{ri} designates the reference pressure that is deemed to supply full requested/reference demand; H_t is the pressure threshold above which the demand is independent of nodal pressure and a is the exponent of pressure demand relationship.

For the majority of the networks is realistic to distinguish the water demand in PDD and VDD. Additionally, it is necessary to highlight that, in the existing software, is not feasible to use two separate PDD functions with different consumption rates for simultaneous application at the same network. 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 of water loss (Eq. (10)). The spatial variation of the PDD rate at the model's nodes will be defined by the formation of DMAs and the export of different water loss rate and hence, different PDD rate.

$$PDD_{\Sigma Q} = (PDD_{QWU} * Q_{WU} + PDD_{QWL} * Q_{WL})/\Sigma Q \tag{10}$$

where $PDD_{\Sigma Q}$ represents the PDD rate of the total SIV [%]; PDD_{QWU} and PDD_{QWL} represents the PDD rate of the water uses and the real losses volume, respectively, [%]; Q_{WU} and Q_{WL} are the water uses and the real losses volume, respectively [m^3]; ΣQ is the SIV [m^3].

As mentioned above, the separation of demand is useful for more accurate simulation and for exporting results more close to the reality. VDD is considered to be consumptions which depend on the required volume of water and are independent of pressure, such as dishwashers, washing machines and toilets. On the contrary, PDD is considered to be consumptions which depend on pressure, such as the use of shower and losses due to leaks and breaks. For the better modeling of the WDS, the separation of various consumptions in PDD and VDD and evaluation of the demand's rate, that is, pressure dependent is needed. There are several studies [24] worldwide that calculated the percentage of each individual's usage of household consumption (Fig. 4). Fig. 5 presents the main components of the residential water use in Greece. They are pretty similar to the findings of the international literature (Fig. 4). In Kos case, the daily residential water use was divided into three types: personal hygiene (i.e. shower, bath, washing hands), toilets and other uses representing 36, 27 and 37% of the total consumption, respectively. Then, for each of these sub-uses the PDD and/or VDD parts were identified (Table 2), resultingin the respective portions, regarding the total residential water including both the authorized and the unauthorized uses. Regarding the water losses' nature, studying their components (Table 3), it was assumed that the majority is classified

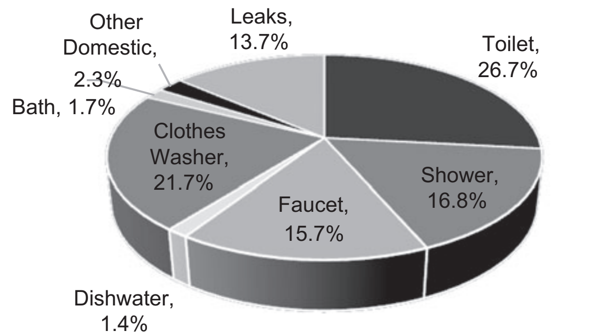

Fig. 4. Indoor per capita use percent by fixture, 12 study sites.

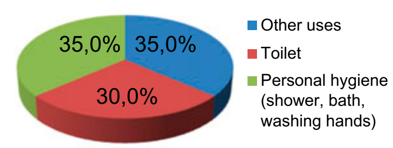

Fig. 5. Typical water in-house use in Greece [15].

Table 2
Classification of water use in PDD and VDD

Residential water uses in Kos	(%)	Classification
Personal hygiene (bath, shower)	36	PDD
Toilet	27	VDD
Clothes washer, dishwasher	18	PDD/VDD
Potable water	4	VDD
Garden, car washing, other uses	15	PDD

Table 3
Water Balance of Kos Town (2008)

Volumes	(m^3)	(%)
System Input Volume	3.136.699	100
Billed Authorized Consumption	1.881.999	60.0
Unbilled Authorized Consumption	66.000	2.1
Apparent Losses	188.202	6.0
Real Losses	1.000.497	31.9
Water Losses	1.188.699	37.9

as almost fully pressure dependent. Finally, the PDD rate of total use, reached 70.5%.

2.5. Installed devices combination

The pressure management in the model's network was achieved "installing" virtual PRVs. There are three types of PRVs commercially available, the fixed outlet PRV, the multi-point control modulated PRV and the flow modulating PRV. At the present simulation study, the first type was used, which, regardless of the upstream water pressure, regulates the downstream pressure to a predetermined constant value. The "multi point control modulated PRV" was also used, which constitutes a more sophisticated form of fixed PRV, as it contains internal timer. Thus, enables the user to configure the temporal variation of the valve opening based on demand profile data. The third type, flow modulating PRV, was not used as it was not possible to be directly simulated using the specific software. The main objective of any scenario checked was to reduce (by virtually installing PRVs and pumps/boosters) the average operating pressure in each DMA, keeping it over the minimum accepted level (threshold) at the critical system nodes (where the operating pressure is the lowestone during the day time). This pressure threshold is two atmospheres (or about 200 kPa). The following four groups of scenarios were checked.

1stscenario: this set of scenarios used only fixed PRV. Utilizing the network's model for each scenario, tests were performed until the nodal pressures downstream of the PRV were such so that the corresponding pressure at the critical system node (critical point) in any DMA to approximate 2 atm, remaining greater than this value. Pressure approached the threshold, as expected, only two times in 24 h.
2ndscenario: this set of scenarios used only 24 h modulated PRVs that gave the possibility to change the downstream pressure throughout the day, based on each case pattern. The PRVs initial pressures were similar to those of the 1st set scenario, apart from very few exceptions, while with the valve patterns introduced a relative stability of the diurnal nodal pressures was achieved, with the critical point showing steady pressure of 2 atm during the day.
3rdscenario: this set of scenarios refers to the combined use of "fixed outlet" PRVs with local pumps. The reduction of the PRVs' initial pressure below the value found in the first set of scenarios, resulted in a further average pressure drop for all nodes in each DMA. Unsurprisingly, the pressure at the critical points (and probably at other neighboring nodes) dropped further. Those values were below the threshold imposed by the regulation. To restore the pressure at acceptable levels in any node required local pumps, which were also virtually installed.
4thscenario: this set of scenarios is similar to the third one except that modulated (24 h) PRVs were used instead of "fixed outlet" ones.

The selection of appropriate equipment is related to the choice of the most efficient and economic scenarios of the study. A proper cost-benefit analysis has to include incoming water savings and the beneficial effect of the pressure drop in the system's equipment, while the costs have to include the investment costs required to acquire and install the necessary equipment (fixed PRVs, 24 h modulated PRVs, pumps) and the additional electricity cost. Regarding the pumps modeling, they were simulated as simple (1 point) centrifugal pumps with a nominal head so that the pressure at the critical point of each DMA exceeds 200 kPa. The specified maximum number of pumps was equal to 3 per DMA. The optimal PRVs location and settings were found by trial and error.

3. Results and discussion

3.1. Scenarios results

Pressure management through the formation of DMAs and installation of PRVs led to significant findings and results. The network was resolved for year 2008, for which a complete data-set from a previous study was available [25]. The total SIV was significantly decreased both in terms of the revenue water (actual water consumption) and of the non-revenue water (water losses). More specifically, the pressure reduction ranged from 29.18 to 56.45%, while the water consumption was reduced from 12.22 to 24.15%. Fig. 6 presents the value of the mean pressure per DMA for the six scenarios (initial status, DMAs formation and the 4 equipment application scenarios) during the first and the fourth billing (bimonthly) period, while (Fig. 7) presents the rate of SIV in all DMAs for all scenarios checked during the same billing periods. The results in each DMA look alike during all billing periods.

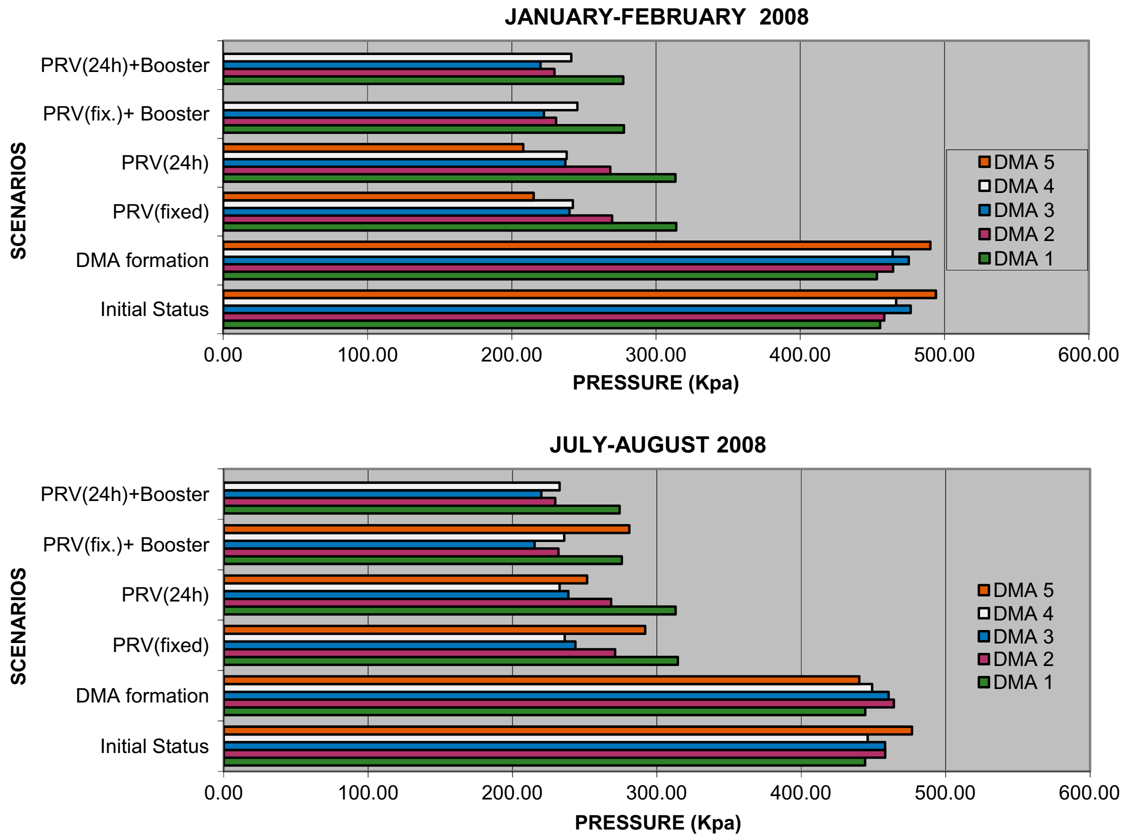

Fig. 6. The average pressure of the DMAs in 1st and 4th billing periods (bimonthly) of 2008 for all scenarios considered.

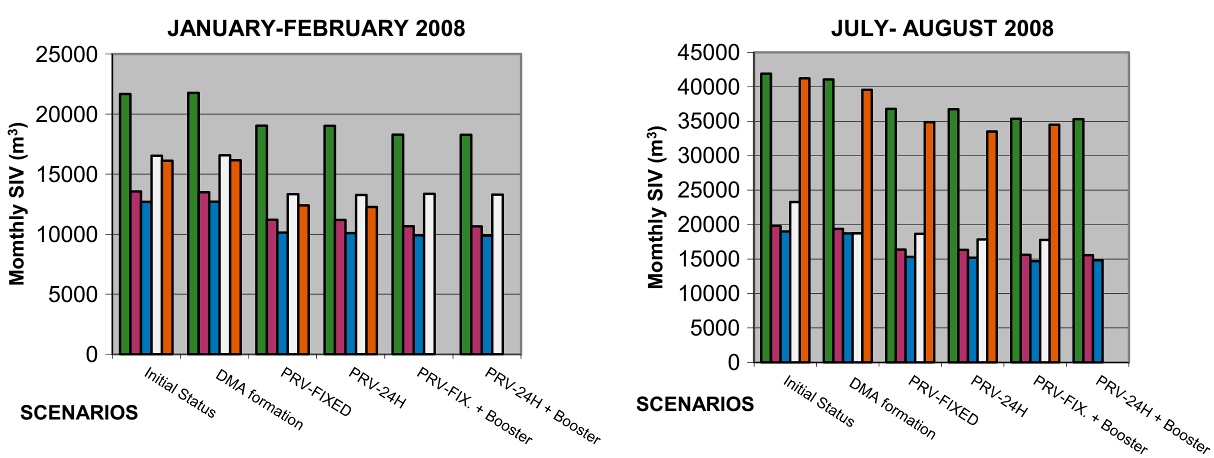

Fig. 7. Monthly water consumption per DMA in the 1st and 4th billing period (bimonthly) of 2008 for all scenarios considered.

3.2. Selection of best scenarios

To select the best scenarios, the estimation of the annual profit was required, so that there is an overall perspective on each scenario's efficiency (Table 4, Fig. 8). More specifically, the full water cost (including direct, environmental and resource cost) obtained, is equal to 1 €/m^3 which is clearly more expensive than the current cost, but reflects the approximate full

Table 4
The annual profit (€) resulting from the application scenarios

DMA		PRV (fixed)	PRV (24 h)	PRV (fixed) +pumps	PRV (24 h) +pumps
DMA 1	Annual benefit (€)	21,785	21,893	27,998	28,116
	Annual cost (€)	569	1,868	719	2,018
	Annual profit (€)	21,216	20,025	27,278	26,099
DMA 2	Annual benefit (€)	17,769	17,949	21,718	21,911
	Annual cost (€)	229	870	379	1,020
	Annual profit (€)	17,540	17,079	21,340	20,891
DMA 3	Annual benefit (€)	18,738	19,079	20,834	20,955
	Annual cost (€)	750	2,250	900	2,400
	Annual profit (€)	17,988	16,829	19,934	18,555
DMA 4	Annual benefit (€)	23,474	23,924	24,396	24,829
	Annual cost (€)	695	2,355	845	2,505
	Annual profit (€)	22,779	21,569	23,551	22,324
DMA 5	Annual benefit (€)	29,819	33,066	–	–
	Annual cost (€)	569	1,868	–	–
	Annual profit (€)	29,249	31,198	–	–
Total	Annual benefit (€)	111,584	115,910	128,012	128,876
	Annual cost (€)	2,812	9,210	4,710	9,810
	Annual profit (€)	108,773	106,700	123,302	119,066

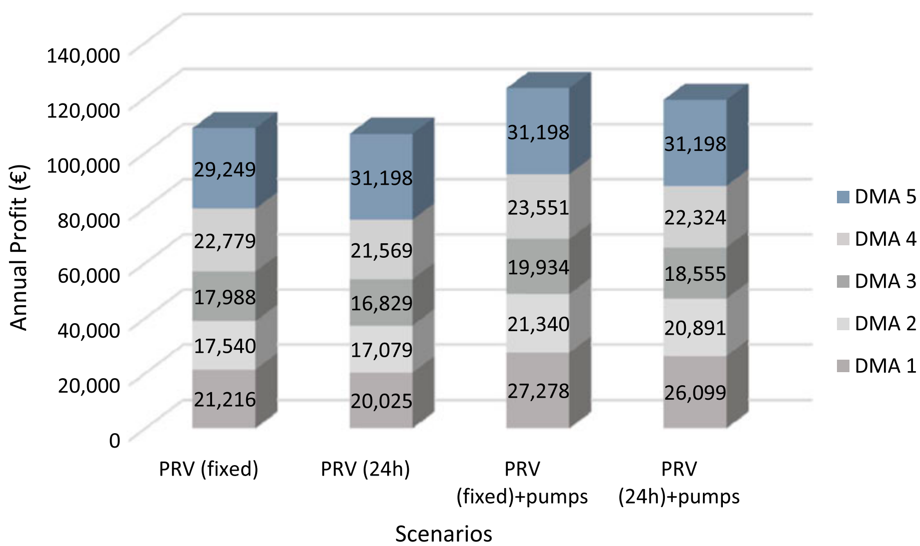

Fig. 8. The annual profit (€) resulting from the application scenarios.

water cost. The unit cost of the energy used for the pumps' operation (based on DEYAK records) is 0.1036 €/kWh. The costs of PRVs' installation were based on the nominal diameter of the pipe they are applied to. A fixed PRV's cost ranges from 1,463€ to 3,750€ for diameters from 90 to 200 mm, and a 24 h modulated PRV's cost ranges from 5,640 to 11,250 €, respectively. The cost of pumps is 500 € for small and medium diameter pipes and 1,000 € for water mains. Those prices are indicative market prices, depending on the type, special characteristics and brand of the equipment. All devices' life cycle is taken to be 10 years (according to the national Law may range from 10 to 14 years), during the estimation of their annual depreciation costs. Regarding the annual profits' calculation of the sum of the DMAs, for the last two scenarios the benefit, cost and profit values were equal to the values of the "PRVs 24 h" scenario. This is because of the particularity of DMA 5, where it was not effective to install pumps.

3.3. 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) [21]. The multiplicatively weighted (MW) Voronoi diagram is defined when the distance between pointsis multiplied by positive weights in contrast to the typical Voronoi diagram, where the only factor is the distance [26]. Applying the MW-Voronoi diagrams process, the model nodes were used in dividing (in polygons) the area of Kos Town served by the WDS. To result to a better perspective of the actual circumstances, since these polygons were not reflect areas of equal water demand, weighted factors have been assigned to each polygon [21]. The two factors used were residential coverage and buildings' height of each polygon area. For the comparison of the two methods, the water demand appointed to each node was expressed as percentage of the WDS's total demand.

Cases from all three categories of water meters' groups were checked and the general conclusions are: (a) SAWDSL method results in smaller water demand

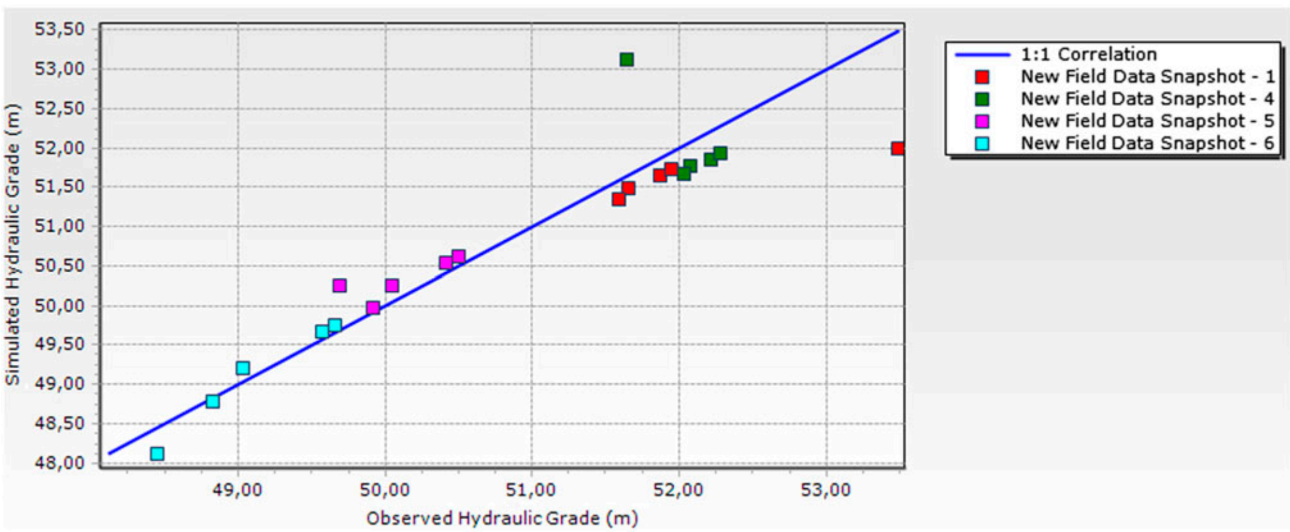

Fig. 9. Correlation between observed and simulated HG in SAWDSL method.

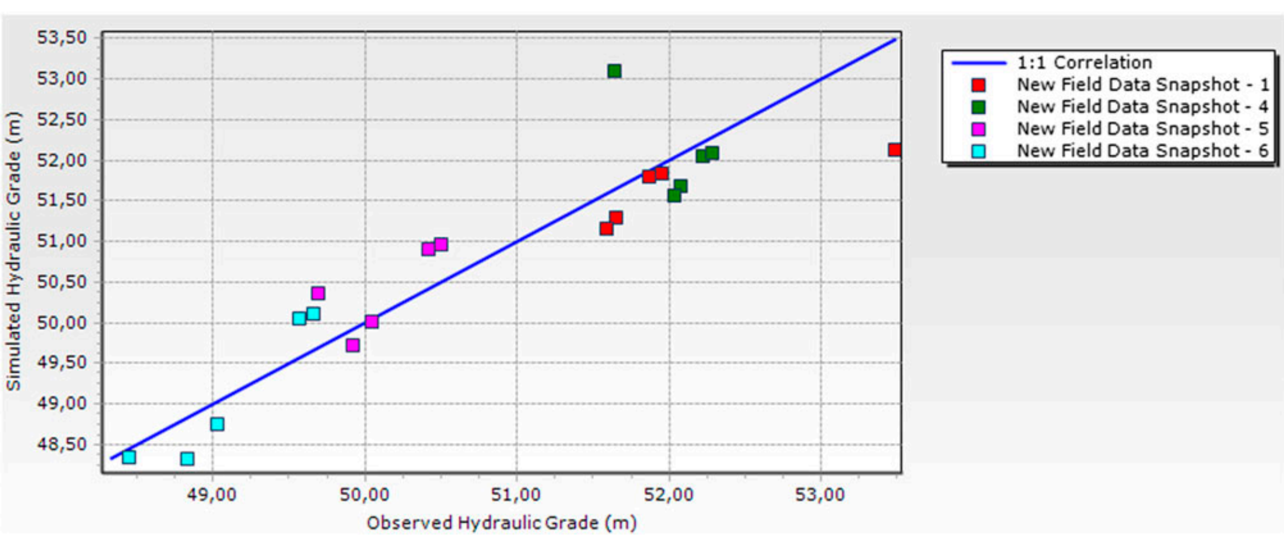

Fig. 10. Correlation between observed and simulated HG in Voronoi method.

values at nodes located inside the town limits compared to Thiessen method. The differences are smaller than 2%; (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 the suburban nodes (few dozen) [21]. (Figs 9 and 10) present the correlation between observed and simulated hydraulic grade of SAWDSL and Voronoi methods, respectively. These are resulted from the calibration study of the model. SAWDSL method resulted in 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.

4. Conclusions

In Kos WDS, since the necessary data and money were not available, a method (SAWDSL) which allocates the water demand at street level was preferred for the hydraulic simulation. Its outcome was compared to that of the Voronoi diagrams method and to field measurements. The calibration process showed that there were significant differences among the recorded pressures. To eliminate the difference between the Voronoi method's model and the reality, additional specific factors (e.g. residence type, education level, etc.) should be considered when developing the method's weighted factors. Using the SAWDSL method, the demand allocation 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 determination of the PDD and VDD parts of each water demand is very useful during the modeling process and is mainly to do with efforts to reduce water loss through pressure management practices.

Kos WDS model was resolved for 132 different scenarios, searching for the proper pressure management and the corresponding water consumption reduction. There were 20 (5 DMAs x 4 equipment application scenarios) different scenarios for each bimonthly billing period apart from the initial status and the status of formated DMAs scenarios. The reduction in water consumption achieved ranged between 12% for scenarios with fixed PRVs installed, up to 25% for scenarios with 24 h PRVs and pumps installed. Considering the cost-benefit analysis for the first four DMAs, the highest water savings refer to the "fixed PRVs plus local pump" scenario. DMA 5 is more complicated (in terms of network's morphology) requiring more than three pumps to be installed making, thus, the scenario of the 24 h PRVs as the most profitable one. The total annual profits were equal to 108,773 € for "fixed PRVs" scenario, 106,700 € for "PRVs 24 h" scenario, 123,302 € for "fixed PRVs + pumps" scenario and 119,066 € for "PRVs 24 h + pumps" scenario. The total annual water savings were calculated to 127,090.14 m^3. The average pressure of DMA was decreased between 29.18 and 56.45%, followed by uniform distribution in all two-month periods. These outcomes persuaded the local water utility in Kos Town to proceed with the actual implementation of the pilot study by tendering and finally installing the necessary system devices/equipment in more than 40 manholes across town.

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