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# A new performance analysis model for urban water supply systems evaluation

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**ABSTRACT**

Non-revenue water (NRW) is among the performance indicators that have a great importance in urban water distribution systems. In this study, the probability statistical approach used to compare the temporal variations of the non-revenue water rate (NRWR) and a new performance evaluation chart have been suggested for practical use of the NRWR. The NRWR's probabilistic occurrence frequency and the statistical analysis provide a criterion for the performance evaluation and improvement of operating conditions. The NRWR performance indicator evaluation has been made for three periods of 12 districts in Kocaeli by considering the risk level. According to the study results, in the 2013–2015 periods, the performance of the Dilovası, Gebze, and Kartepe districts has improved significantly compared to the 2010–2012 periods. Başiskele and İzmit have the highest performance level in the last period following Kandıra. It will be possible to ameliorate the NRWR of districts in the future periods through the suggested site-specific model analysis and prioritize the plans by sampling the good district practices.

*Keywords:* Water supply systems; Non-revenue water; Risk analysis; Performance analysis

## 1. Introduction

Water utilities try to transfer the quality potable water in accordance with standards for miles and miles through water distribution systems (WDSs). However, the illegal connections, breaks, leaks, unauthorized non-metered water use, and water meter measurement errors cause significant water losses in current water distribution systems [1]. Thus, the operating cost increases, and the water and service quality reduce. On the other hand, making network connections to meet the water demand of rapidly increasing population density with urbanization in addition to the existing potable water distribution systems brings low-pressure problems in its wake [2]. Therefore, the additional network transfers from different isolated zones to the existing distribution systems aim to increase the water flow lead and increase the operating pressure and the real water losses.

The water utilities should develop effective improvement strategies to prevent all kinds of water losses, ensure productive, economic, and sustainable network management, and overcome network pressure problems. Consequently, it is important to prioritize the investments to be made according to the budgets of water utilities by giving the right decisions [3].

The International Water Association (IWA) and the American Water Works Association (AWWA) have made significant suggestions on water audit tools and methodologies to evaluate the WDSs performances. These consist of performance indicator databases and water balance assessments [4]. The IWA has made suggestions on the 170 performance indicator databases and water balance components by considering the 232 variables that may be required to monitor and measure the water distribution system [5,6]. The groups regarding performance indicators used by water

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utilities to evaluate their water distribution systems are available in Table 1.

The performance indicators used to determine and evaluate the current situation of water distribution systems are frequently preferred and well-known effective indices. According to the literature review, some researchers have studied the performance indicators suggested by the IWA [7–9]. The performance indicators proposed by the study of Alegre et al. [10] are available in Table 2.

Water utilities have occasion to evaluate the performances of water distribution system analyzing these indicators through the various models and analysis methods. In a study conducted in Kocaeli city, the performances of 12 districts in the 2017–2018 periods have been evaluated directly through the models formed by using the non-revenue water (NRW) data [11]. Also, some researchers have conducted studies on water budget components and performance indicators, according to the literature review [4,12,13].

The non-revenue water rate (NRWR), among these indicators, is significant for the determination and comparison of urban water distribution system performances in different periods. The NRW rate is obtained by division the non-revenue water amount ($m^3$) into the system input volume ($m^3$). In addition, the data quality, frequency, and reliability have importance for using the water budget balance in a correct way [14]. It is one of the key issues for water balance

Table 1
IWA performance indicators [5]

| Indicators and numbers | | | | | |
|---|---|---|---|---|---|
| **Water resources/WR** | **4** | **Operational/Op** | **44** | **Financial/Fi** | **47** |
| **Quality of service/QS** | **34** | Inspection and maintenance of physical assets | 6 | Composition of running costs per type of costs | 5 |
| Service connections and meter, installation and repair | 3 | Instrumentation calibration | 5 | Costs | 3 |
| Service coverage | 5 | Vehicle availability | 1 | Revenues | 3 |
| Pressure and continuity of supply | 8 | Electrical and signal transmission equipment inspection | 3 | Composition of running costs per technical function activity | 6 |
| Customer complaints | 9 | Mains/valves/service connections rehabilitation | 3 | Composition of running costs per main function of water undertaking | 5 |
| Public taps and standpipes | 4 | Inspection and maintenance of physical assets | 2 | Investment | 3 |
| Quality of supplied water | 5 | Pumps rehabilitation | 2 | Average water charges | 2 |
| **Personnel/Pe** | **26** | Operational water losses | 7 | Efficiency | 9 |
| Personnel health and safety | 4 | Failure | 6 | Leverage | 2 |
| Personnel per main function | 7 | Water metering | 4 | Liquidity | 1 |
| Personnel qualification | 3 | Water quality monitoring | 5 | Profitability | 4 |
| Total personnel | 2 | **Physical/Ph** | **15** | Economic water losses | 2 |
| Personnel training | 3 | Treatment and storage | 3 | Composition of capital costs | 2 |
| Technical services personnel per activity | 6 | Pumping | 4 | | |
| | | Transmission and distribution | 2 | | |
| Overtime work | 1 | Meters | 4 | | |
| | | Automation and control | 2 | | |

Table 2
Water loss PIs [10]

| Group | PI | Measure | Notation |
|---|---|---|---|
| Economic and financial | Non-revenue water | NRW by volume (%) | Fi46 |
| | | NRW by cost (%) | Fi47 |
| Water resources | Water resources | Inefficiency of use water resources (%) | WR1 |
| Operational | Water losses | $m^3$/service connection/y | Op23 |
| | Apparent losses | Apparent losses (%) | Op25 |
| | | Apparent losses (%) | Op26 |
| | Real losses | liters/service connection/d | Op27 |
| | Infrastructure leakage index | – | Op29 |

calculations since the water utilities do not keep regularly the necessary data records [8].

It is estimated that the NRW amount is at the level of 346 million $m^3$ daily and 126 billion $m^3$ annually around the world [15]. The NRW rates of developed countries are at low levels; Lithuania 21%, New Zealand 24%, United States 13%, Singapore 4%, Belgium 21%, Denmark 7% in contrast to the high levels in developing countries; Ukraine 36%, Bulgaria 61%, Argentina 42%, South Africa 34%, Hungary 32%, Bosnia and Herzegovina 49% [16].

In Turkey, water losses including the NRW in drinking water supply systems have been calculated as 37,12% (the highest 80%, the lowest 20%) in 2019 [17]. The high rate and its augmentation derive from poor operating activities, inadequate infrastructure, and ineffective planning. A new regulation on "control of water losses in drinking water supply and distribution systems" has entered into force to monitor studies for reducing water losses, encourage the reduction, use water effectively, and prevent wastage [18]. Metropolitan water utilities work hard to reduce the NRWR up to 30% by 2023 and up to 25% by 2028 within the scope of this regulation. If water losses reduce the NRWR up to 25%, 454 million $m^3$/y water-saving throughout the country and 1,587 million dollars financial income are expected as a result of this saving [17].

The age, pipe type and length of the water distribution system, service connection length, operating pressure, water meters, real water losses, administrative and environmental factors have an impact upon the NRWR. It is possible through the pipeline and assets management, pressure management (PM), district meter area (DMA), active leakage control, speed and quality of repairs, etc. to minimize the uncertainties such as leakage activities, failure in troubleshooting in a short time as well as high network pressure that directly influence real water losses which are the most important component of the NRW [19–21].

Water utilities try many methods to reduce the NRWRs. For example, district metered area (DMA), active leakage control method, and PM studies in water distribution systems to reduce real losses by controlling them. Monitoring and controlling the minimum night flow in water distribution systems through the SCADA system for 24 h is quite important. The other important parameter on the NRW is apparent losses including meter measurement and reading errors besides unauthorized water consumption. The most effective method to be applied to reduce these losses in the NRW is the replacement of end-of-life water meters with measurement errors. Many studies have been conducted about the optimum replacement time in accordance with the meterage and the quantity of water passing through the meter [22–24]. On the other hand, the replacement of old and constantly breaking down infrastructures and the prevention of illegal connections on the networks are the activities reducing significantly the NRW losses. Water utilities should reduce their high NRW levels through the activities to be planned in accordance with their budgets by taking into account the cost, performance, and reduction achieved by the practices. For this purpose, it is required to evaluate the NRW reduction performances through scientific and analytical approaches.

Hydraulic model studies have been conducted to reduce the NRW in Kos (Greece) and Antalya (Turkey) regions [25]. The researchers have emphasized that the integrated methodology should be applied step by step to overcome the NRW problem. Boztaş et al. [26] have applied the minimum night flow and the active leakage control methods to prevent the leakages in service connections affecting the NRW in the water distribution system of Malatya Water and Sewerage Administration (MASKİ). Approximately 148.9 L/h water saving has been achieved in 14 DMAs with the help of the applied methods. Şişman and Kizilöz [27] have developed NRWR prediction models through the artificial neural network (ANN) and Kriging methods by using water distribution system variables such as mean age of pipe, network length, mean pressure network, mean diameter of pipe, and system input volume (SIV). In another study, a trend-risk model has been proposed to predict the NRWR [18]. Forecasting, controlling, reducing the NRW amount, and evaluating its performance is among the most significant issues to effectively use water resources reducing the effects of climate changes.

In general, statistical methodologies are preferred for uncertainty calculations. However, a detailed evaluation can be made only by probabilistic methods according to the risk level [28]. In this study, beyond classical approaches, the performance evaluation of different districts has been analyzed through a probabilistic methodology based on risk models and a new performance chart. The practice effects on the performance and the efficiency of the planned investments have been analyzed through the suggested performance charts by evaluating the amounts of investments made in three different periods in accordance with the NRWR risk model results. The main objective of this paper is to suggest a new model approach in order to assess the impact of studies on performance to reduce the NRWR. The use of the suggested methodology and its interpretation with infrastructure expenditures makes also available a policy-related contribution for decision-makers.

## 2. Study area, general evaluation, and data

Kocaeli is an industrial city situated in the Marmara Region of Turkey (Fig. 1). It is a port, which has a coast on the Black Sea and İzmit Gulf, and its population is increasing day by day in accordance with the advancing industry. The water demand of the increasing population is provided by ISU (Kocaeli Water and Sewerage Administration).

The existing water distribution systems are composed of different pipe types such as polyvinyl chloride (PVC), high-density polyethylene (HDPE), asbestos, ductile font (DF), polyethylene (PE), cast iron, and steel, etc. [18]. The overall length of the potable water distribution network operated in the Kocaeli city is 8,936 km and the total water consumption is 163,627,918 $m^3$ for the year 2018 [27]. In this study, the used operational parameters such as SIV, pipe length, operating pressure, pipe age, mean pipe diameter, no. of consumers, and the NRWR are presented in Table 3 for 12 districts.

The occasional drought arising out of precipitation below seasonal averages is observed in Kocaeli in every 8–10-year time period. During the last months of the year 2006, the drought had even more influence over the city and water demand was supplied intermittently in a period of


Fig. 1. Districts in Kocaeli.

Table 3
Operational details for districts in 2018 [27]

| District | SIV | Pipe length | Operating pressure | Pipe age | Mean pipe diameter | No. of consumers | NRWR |
|---|---|---|---|---|---|---|---|
| | ($10^5 \times m^3$) | (km) | (m) | (y) | (mm) | (number) | (%) |
| 1 | 30.8 | 1,114 | 54 | 12 | 134 | 160,135 | 29.74 |
| 2 | 6.6 | 1,600 | 56 | 14 | 121 | 32,487 | 34.05 |
| 3 | 14.1 | 918 | 43 | 19 | 159 | 51,962 | 44.36 |
| 4 | 14.7 | 680 | 58 | 30 | 125 | 66,121 | 32.28 |
| 5 | 29.8 | 1,050 | 64 | 16 | 144 | 147,275 | 25.40 |
| 6 | 8.9 | 854 | 53 | 22 | 119 | 43,254 | 28.50 |
| 7 | 14.2 | 803 | 60 | 24 | 124 | 70,595 | 37.02 |
| 8 | 5.1 | 443 | 45 | 27 | 108 | 29,018 | 41.10 |
| 9 | 11.1 | 447 | 47 | 26 | 125 | 55,088 | 40.11 |
| 10 | 6.2 | 310 | 51 | 18 | 125 | 15,471 | 26.16 |
| 11 | 9.4 | 339 | 49 | 8 | 133 | 49,244 | 23.01 |
| 12 | 12.2 | 378 | 57 | 25 | 121 | 75,927 | 26.01 |

20 days. Recently, during the last drought that occurred in 2014, water supplement has been provided from the Sapanca Lake, one of the largest water sources in the region, as well as from wells and local alternate water sources. As Kocaeli is a city experiencing droughts from time to time, it is significant to introduce some strategies through scientific models to provide water supply for its increasing population and prevent water losses. Therefore, within the scope of this study, it is aimed to regulate the operation-maintenance activities and prioritize the investments by close monitoring and evaluating the performances of non-revenue water rates through mathematical models.

The standard water balance table of Kocaeli city is available in Table 4. In this table, real losses are higher than apparent losses. The mains and service connections leakages have a significant rate in real losses with 24.63%. The water utilities in Kocaeli city have preferred the active leakage control and pressure management system to reduce this rate. On the other hand, end-of-life water meters with faulty measurements have been replaced to reduce the authorized consumption error rate in apparent losses corresponding to 4.85% of the NRW total amount.

The NRWR change of 12 districts in Kocaeli can be seen in Fig. 2 for the years 2010–2018. The NRWRs of Çayırova,

Table 4
Water balance components of Kocaeli in 2018 [27]

| | | | | |
|---|---|---|---|---|
| System input volume (SIV): 163,627,918 $m^3/y$ 100% | Authorized consumption: 69.18% | Billed authorized consumption: 67.69% | Billed meter consumption: 67.35% | Revenue water: 67.69% |
| | | | Billed unmetered consumption: 0.34% | |
| | | Unbilled authorized consumption: 1.49% | Unbilled meter consumption: 0.64% | Non-revenue water: 32.31% |
| | | | Unbilled unmetered consumption: 0.86% | |
| | Water losses: 30.82% | Apparent losses: 6.03% | Unauthorized consumption: 1.18% | |
| | | | Authorized consumption errors: 4.85% | |
| | | Real losses: 24.79% | Leakage and overflows at storage tanks: 0.16% | |
| | | | Leakage on transmission and distribution mains and service connections: 24.63% | |

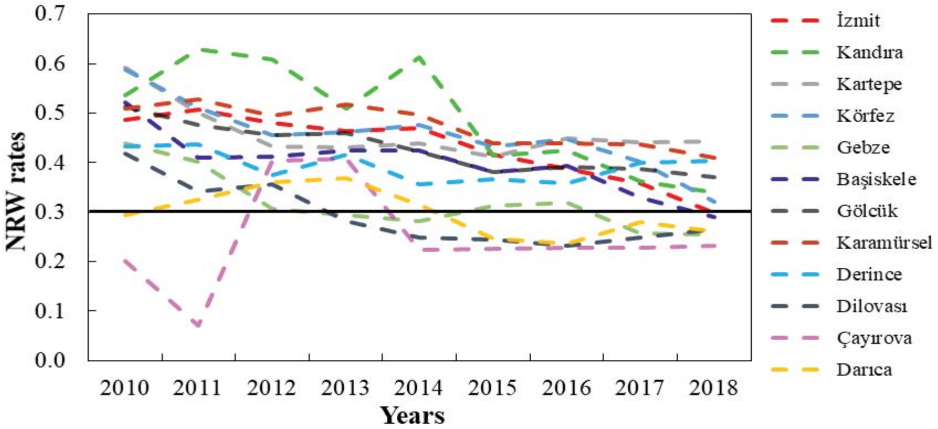


Fig. 2. NRW rate change of 12 districts in Kocaeli.

Darıca, Gebze, and Dilovası are below the level of 0.30 at the end of 2018, the target value for the end of 2019 in accordance with the relevant regulations. Although the two districts approach the average, the NRWR of 8 regions is still above the average. The NRWRs of Derince, Gölcük, Karamürsel, and Kartepe districts have been above the 0.40 average in recent years and virtually unchanged. Each region has a different water distribution system, water consumption patterns, seasonal change as well as environmental impact, and these affect the NRWRs (Fig. 2).

In the Kandıra district, the NRWR which was over 50% level in the 2010–2014 time period could be reduced up to 34% in 2018 due to the rapid decrease trend created after 2015. Certain activities (for example, district metered area and pressure management) that are applied to prevent real losses are the main reasons for this rapid decrease. Since Kandıra is a rural area, it has dispersed settlements and its total network length is 1,600 km. The DMA and PM activities cannot be carried out rapidly because of this dispersed settlement. On the other hand, the NRWR has been reduced up to 44% in the Kartepe district. However, this last value is high above the targeted 30% level. The pressure management and active leakage control activities are the most important reasons for significant improvement in the NRWRs in the Körfez district [11]. In Gebze, these rates have been reduced in the 2016–2018 period up to 25% through the DMA and meter replacement activities. Since a significant part of the water distribution systems of the districts Dilovası and Çayırova has been replaced in the years 2010–2012 and 2016–2018 respectively, the NRWRs have been reduced at 30% level. In the Darıca district, the most important reason for the low level under 30% in NRWRs is to use DF pipes. Despite the activities made, the NRWR has been at 40% level for many years in the Derince district, therefore the entire infrastructure is planned to be replaced by the utility through the investment program.

The NRWR changes of four districts have been analyzed in detail from 2010 to 2018 through the chart given in Fig. 3. In the İzmit district, the NRWR, which was at 0.47 level in 2014, reduced up to 0.3 in 2018 thanks to the hydraulic model studies with real losses minimization. In this district, the minimum night flows have been monitored through the SCADA system by forming district metered areas (DMAs) in the water distribution system. The failure detection has been made with the help of the active leakage control method beginning from the DMAs. The high night flow, maintenance, and repair activities have been planned at designated points to reduce leakages. The network pressures have been adjusted through pressure management applications to control and reduce the current leakages and undetected failures. On the other hand, the old infrastructure within the DMAs that fail frequently has been replaced partially. Furthermore, the entire water meters have been replaced to minimize apparent loss components that have an impact on the NRW in addition to the

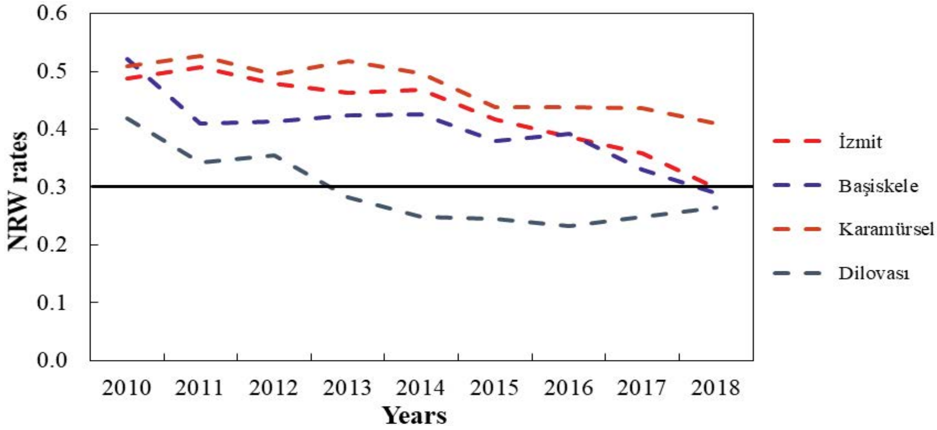


Fig. 3. NRWR changes of İzmit, Başiskele, Karamürsel, and Dilovası.

studies on reducing real losses, thus the losses arising out of meter errors have been also minimized.

Dilovası, the other district in the chart, is the smallest district of Kocaeli city, it has 15,471 consumers [29]. The NRWR of this district was measured as 0.36 in 2012 and minimized to 0.23 in 2016 following the infrastructure replacement with approximately 206 km HDPE pipes, however, the NRWR increased again to 0.26 at the end of 2018.

Finally, the NRWRs decreased to 0.41 in Karamürsel and to 0.29 levels in Başiskele in 2018 while these rates were nearly the same in the 2010 time period. The NRWR has not nearly changed in Karamürsel after 2015. In this district, about 29,000 outworn meters have been replaced by new meters including a remote reading system to reduce apparent losses [11]. Also, it is aimed to prevent illegal water use by moving water meters of greenhouses, farms, and villas to the parcel entry points. Despite the fact that the apparent losses have been reduced in Karamürsel, the NRWR is still high due to the absence of real losses studies. On the other hand, the real losses have been considerably minimized in Başiskele after 2016 through the pressure management (PM) application performed in areas in which outdated water distribution systems have frequently failed. It is clear that the studies on prevention of illegal water use and the replacement of outworn water meters in the district use have supported the NRWR improvement.

The data used in this study has been obtained from the standard water balance table suggested by the IWWA/AWWA. The water has been supplied in Kocaeli city from deep wells, local resources, the Sapanca Lake, the Yuvacık and Namazgah Dams [30]. The water transmitted to the 12 districts after treatment is measured firstly through the ultrasonic flow meters located at the tank entrances, and then the SIVs are determined. The revenue water value is calculated by summing up the billed authorized consumption amount of each consumer. The difference between the SIV and the revenue water amount indicates the total NRW value. The unbilled authorized consumption amount that is one of the significant uncertainties in the NRW is calculated by taking into account unbilled metered and unbilled unmetered consumptions. The unbilled metered consumption includes the accrued but not unbilled water usage of certain consumers such as religious facilities, fountains, cemeteries, etc. On the other hand, the unbilled unmetered consumption is calculated by considering the pipe diameters and average velocity depending on network and service connection failures. The difference between the current consumer number and the independent section number in authorized buildings obtained through the geographical information system (GIS) has been taken into account in the unauthorized consumption amount calculation. Finally, authorized consumption error values are calculated by testing water meters of different diameters, models, and ages, and their measurement accuracy is determined in the Weight and Measures Center of the Ministry of Industry and Trade located in Kocaeli city [27].

## 3. Methodology

The NRWRs are generally high in developing countries due to insufficient management investments and the replacement of water distribution systems. When the WDS is analyzed in terms of the NRW, it is clear that there are increases depending on uncertainties in infrastructures. The classical deterministic approaches used in the NRW analysis make it difficult to achieve a reliable performance evaluation and estimation due to uncertainties. For such type uncertainties, the stationary and non-stationary stochastic process analyses can be used in water distribution systems. The suggested models that have an effect upon the NRWR performance evaluation of WDSs have been used through the probability statistical approach with risk parameters and through a new performance chart defined in this paper.

While the uncertainties are described as non-digitizable events, the risk is described as digitized random variables [31]. The risk, $r$, is identified as the probability variable which is greater than the critical level (nationally or internationally allowable levels), $C_L$, at least one over the time, $T_r$, of consideration [32]. In this study, the risk ($r$) is the probability $P$ and the NRWR will be higher than a given threshold named the critical NRWR value. The $\text{NRWR}_c$ is given in Eq. (1). The risk-reliability relationship is given as follows (Fig. 4) by taking as a reference the NRWR diagram and critical value.

The risk statements according to the definitions given above are obtained through Eqs. (1)–(3). The basic definition of classical risk proposed by [33,34] is as per the following:

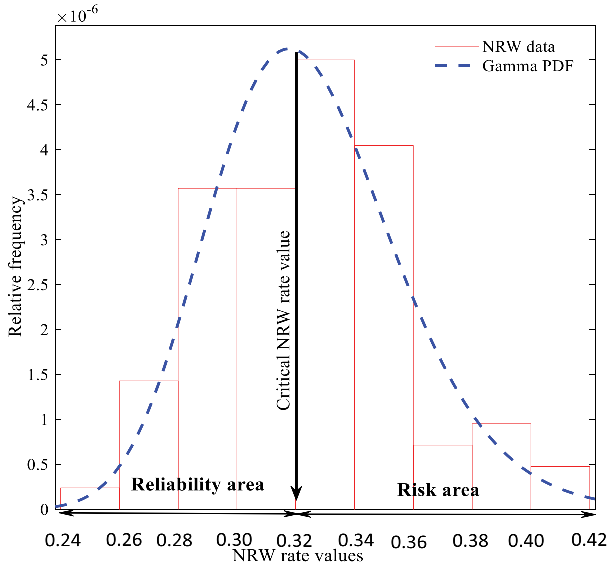


Fig. 4. Risk-reliability relationship for NRW rate values.

$$\text{Risk}(r) = P(\text{NRWR} \geq \text{NRWR}_c) = \frac{1}{T_r} \tag{1}$$

where $T_r$ is observed only once throughout the planned time of any water system [34].

The risk of the "NRWR" event is that the NRWR data equals or exceeds to the described critical level ($\text{NRWR}_c$) [11]. The reliability value of the above-mentioned event is given in Eq. (2).

$$\text{Realibility} = 1 - \text{Risk} = P(\text{NRWR} < \text{NRWR}_c) = 1 - \frac{1}{T_r} \tag{2}$$

If we call $P$ variable as performance variable, then $P(\%)$ can be expressed as follows:

$$P(\%) = \frac{\text{NRWR}_c - \text{NRWR}}{\min(\text{NRWR}_c;\text{NRWR})} \times 100 \tag{3}$$

According to Eqs. (1)–(3):

Decrease performance = $P(\%) < 0$;

Increase performance = $P(\%) \geq 0$;

The 12 districts of Kocaeli have been examined through the methodology given in this section. The performance evaluation of each district has been objectively evaluated through the suggested methodology in accordance with the numerical indicators. The critical NRWR values corresponding to the risk level have been determined by cumulative probability distribution functions (CDF) for performance evaluation.

The steps of risk model and performance analysis are described as follows:

- Firstly, the $\text{NRWR}_i$ values ($i = 1, 2, \ldots, n$) are sorted from the smallest value to the largest so as to generate a risk model chart, and then the order of each data is labeled as $m = 1, 2, \ldots, n$, which is the data number.
- Exceedance probability of each data is calculated according to the following equation by taking into consideration the sorting.

$$P(\text{NRWR} < \text{NRWR}_c) = \left(\frac{m}{n} + 1\right) \tag{4}$$

$P(\text{NRWR} \geq \text{NRWR}_c)$ indicates the exceedance probability of the NRWR data.

- The scatter plots of points formed by using the NRWR data and probabilities mentioned above are prepared. The data is shown on the horizontal axis, the probabilities on the vertical axis for each scatter plot.
- The theoretical probability density functions for scattering are determined by the least-squares method. The model curves are fitted to the most frequently used PDFs or CDFs among the theoretical probability density functions such as Gamma, Weibull, Generalized Extreme Value (Pearson III), Lognormal as well as extreme value (Gumbel).
- The mathematical statements of probability density functions are given below [35,13,28]:

*3.1. Gamma cumulative distribution function*

$$p = F(x|a,b) = \frac{1}{b^a \Gamma(a)} \int_0^x t^{a-1} e^{-t/b} dt \tag{5}$$

In this equation, $\Gamma(a)$ is the Gamma function, $a$ is a shape parameter, and $b$ is a scale parameter.

*3.2. Lognormal cumulative distribution function*

$$p = F(x|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^x \frac{e^{\frac{-(\ln(t)-\mu)^2}{2\sigma^2}}}{t} t^{a-1} dt \tag{6}$$

where the parameters are respectively μ: log mean and σ: log standard deviation.

*3.3. Extreme value distribution (Gumbel)*

$$y = f(x|\mu,\sigma) = \sigma^{-1} \exp\left(\frac{x-\mu}{\sigma}\right) \exp\left(-\exp\left(\frac{x-\mu}{\sigma}\right)\right) \tag{7}$$

where parameters are respectively μ: location parameter and σ: scale parameter.

*3.4. Generalized Extreme Value distribution*

$$y = f(x|k,\mu,\sigma) = \left(\frac{1}{\sigma}\right) \exp\left(-\left(1 + k\left(\frac{x-\mu}{\sigma}\right)^{-1/k}\right)\right) \left(1 + k\left(\frac{x-\mu}{\sigma}\right)^{-1-\frac{1}{k}}\right) \tag{8}$$

In this equation, the location parameter is μ, scale parameter is σ, and shape parameter is $k \neq 0$. $k$: shape parameter $-\infty \leq k \leq \infty$, σ: scale parameter $\sigma \geq 0$, μ: location parameter $-\infty \leq \mu \leq \infty$.

*3.5. Weibull cumulative distribution function*

$$p = F\left(x \middle| a,b\right) = \int_0^x ba^{-b}t^{b-1}e^{-(x/a)^b} I_{(0,\infty)}\left(x\right) \tag{9}$$

Parameters: $a$: scale parameter and $b$: shape parameter

- Finally, the district performances have been analyzed through a new performance evaluation chart for the NRWR according to the identified risk level (50% can be assumed as average). The performance evaluation has also been made according to the expert opinion in percentiles; 1:1 no performance, 0%–10% (very low), 10%–20% (low), 20%–30% (medium), 30%–40% (high) and >40% (very high) based on the NRWR for comparing years (Fig. 5).

## 4. Application

In this study, the NRWR data of 12 districts in Kocaeli have been used for modeling through various probability density functions during three sub-periods 2010–2012, 2013–2015, and 2016–2018.

The appropriate model curves for the NRWR of the İzmit district can be determined through the maximum likelihood estimation (MLE) or the least-squares method. The least-squares method has been preferred for determining the model chart in this study. The fit model curves are available in Fig. 6 in the three sub-periods for İzmit. The probability density function (PDF) model functions and the parameters of the İzmit district are also available in Table 5.

The NRWR value corresponding to the 50% exceedance probability (risk level), we can call this as an average, has been obtained as 0.50 through the model curve according to the 2010–2012 time period. The NRWR of İzmit has been also obtained as 0.45 at the 50% probability of exceedance level for the 2013–2015 time period. The NRW level has declined and the losses have been reduced by a small amount in this time due to the hydraulic model studies in 2014. The NRWR has been 0.35 according to the last period model.

It is seen that the NRWR has been rapidly reduced in the last period, because the DMA and PM applications have been carried out within the scope of hydraulic model studies in addition to the replacement of end-of-life water meters in the DMA to reduce apparent losses. So, the losses caused by meters that have a great influence on the NRWR have been minimized.

The NRWR PDF models of 12 districts in Kocaeli city and the parameters of each function have been given in Table 6.

When the NRWR model charts belonging to the 2010–2012 time period given in Fig. 7 are analyzed, It is obvious that the best model charts are the Pearson PD, Gumbel, and Lognormal PDF. In the 2010–2012 time period, the least NRWR occurred in Darıca district. Dilovası and Gebze are the other districts with the least NRWR following Darıca. The highest NRWR occur in Kartepe, Körfez, Karamürsel, and İzmit, respectively.

The PDF model graphics of the monthly district NRWR data are available in Fig. 8 for the 2013–2015 period. The appropriate model functions have been determined as Gamma, Pearson PD, Weibull, and Log-normal PDFs for the collected data in the districts. In the above-mentioned period, Dilovası has the best NRWR rate, on the other hand, Kandıra has the worst one, according to the models. The evaluation of each district can be made in detail through the model charts given in Fig. 8. Approaching the curves to the vertical indicates that there is not much change in the NRWR amount in the analysis years. If the NRWR value range that the curves scan on the horizontal axis is excessive, it indicates that the NRWR values change frequently over the study years. The district performance can be evaluated by comparison of the previous and next equal time intervals. Approaching the model curve to the left side is an indication of the performance improvement. The most

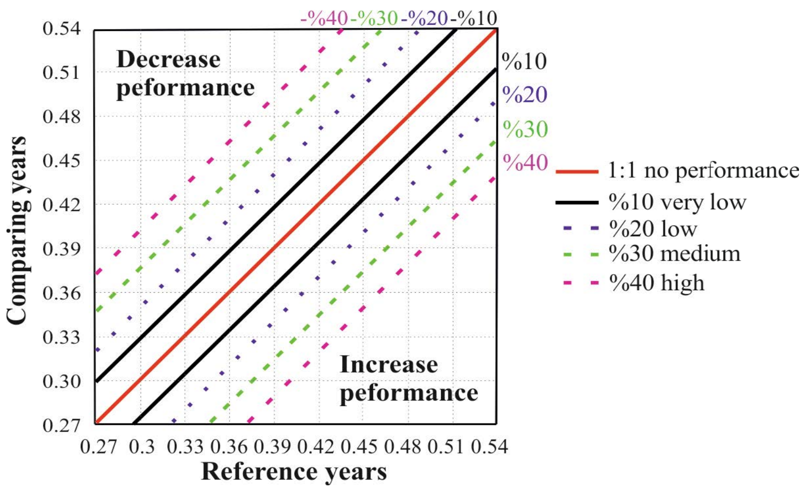


Fig. 5. A new performance evaluation chart for the NRWR.

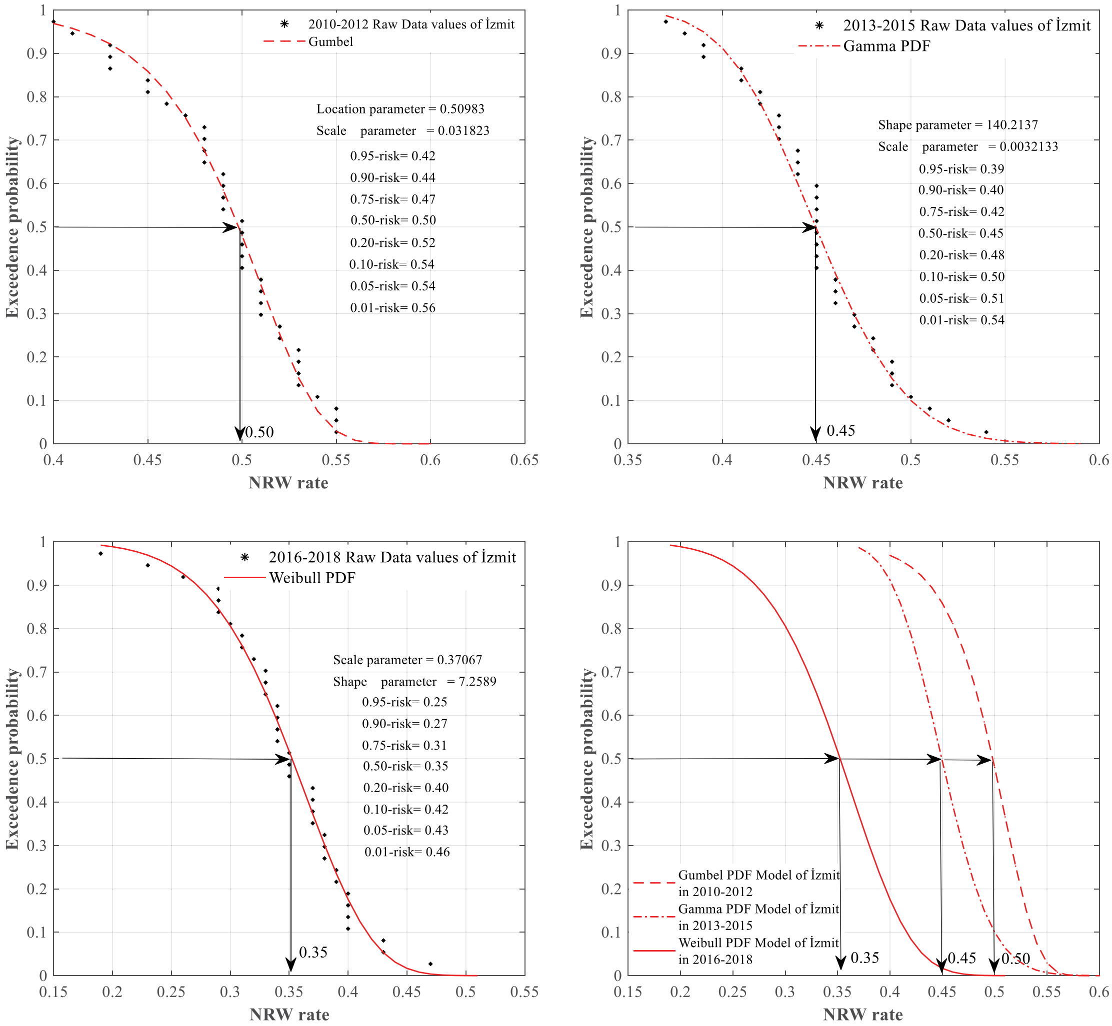


Fig. 6. NRWR and exceedance probability (risk) models of the İzmit district.

Table 5
PDF model functions and parameters of the İzmit district

| PDF | Parameters | 2010–2102 | 2013–2015 | 2016–2018 |
|---|---|---|---|---|
| | μ (location) | 0.509828 | 0.469637 | 0.374383 |
| Extreme value Gumbel | σ (scale) | 0.031822 | 0.037840 | 0.050642 |
| | MLEs | 67.56770 | 63.72350 | 52.47420 |
| | μ (log location) | –0.71316 | –0.800840 | –1.07052 |
| Lognormal | σ (log scale) | 0.082059 | 0.085933 | 0.177487 |
| | MLEs | 65.10330 | 66.59930 | 50.19580 |
| | *a* (scale) | 0.508727 | 0.468062 | 0.370666 |
| Weibull | *b* (shape) | 15.65210 | 12.48020 | 7.258920 |
| | MLEs | 67.66840 | 64.96890 | 53.49870 |
| | *k* (shape) | –0.588131 | –0.266089 | –0.36655 |
| Generalized Extreme Value (Pearson III) | σ (scale) | 0.042822 | 0.037727 | 0.059170 |
| | μ (location) | 0.484009 | 0.436898 | 0.330293 |
| | MLEs | 68.52970 | 66.74870 | 53.04560 |
| | *a* (shape) | 156.0580 | 140.2140 | 35.06470 |
| Gamma | *b* (scale) | 0.003150 | 0.003213 | 0.009918 |
| | MLEs | 65.45770 | 66.68280 | 51.31530 |

Table 6
NRW rate model PDF and parameters of 12 districts in Kocaeli

| District | 2010–2012 | | 2013–2015 | | 2016–2018 | |
|---|---|---|---|---|---|---|
| | Extreme value Gumbel | | Gamma | | Weibull | |
| İzmit | μ (location) | 0.509828 | *a* (shape) | 140.214 | *a* (scale) | 0.370666 |
| | σ (scale) | 0.0318229 | *b* (scale) | 0.00321335 | *b* (shape) | 7.25892 |
| | Extreme value Gumbel | | Lognormal | | Weibull | |
| Darıca | μ (location) | 0.35737 | μ (log location) | –1.1948 | *a* (scale) | 0.27592 |
| | σ (scale) | 0.053461 | σ (log scale) | 0.23016 | *b* (shape) | 6.2249 |
| | | | Generalized Extreme Value (Pearson III) | | Weibull | |
| Kandıra | Not available | | *k* (shape) | –0.63896 | | |
| | | | σ (scale) | 0.124914 | *a* (scale) | 0.416394 |
| | | | μ (location) | 0.521507 | *b* (shape) | 5.89326 |
| | | | Generalized Extreme Value (Pearson III) | | Weibull | |
| Çayırova | Not available | | *k* (shape) | 0.042891 | | |
| | | | σ (scale) | 0.075612 | *a* (scale) | 0.24639 |
| | | | μ (location) | 0.23871 | *b* (shape) | 6.0868 |
| | | | Generalized Extreme Value | | Generalized Extreme Value | |
| | Extreme value Gumbel | | (Pearson III) | | (Pearson III) | |
| Dilovası | | | *k* (shape) | –0.5032 | *k* (shape) | –0.38079 |
| | μ (location) | 0.40909 | σ (scale) | 0.069292 | σ (scale) | 0.046971 |
| | σ (scale) | 0.063484 | μ (location) | 0.24295 | μ (location) | 0.23634 |
| | Generalized Extreme Value (Pearson III) | | Weibull | | Lognormal | |
| Başiskele | *k* (shape) | –0.027197 | | | | |
| | σ (scale) | 0.072245 | *a* (scale) | 0.43799 | μ (log location) | –1.09871 |
| | μ (location) | 0.40484 | *b* (shape) | 6.6912 | σ (log scale) | 0.220475 |
| | Lognormal | | Lognormal | | Weibull | |
| Gölcük | μ (log location) | –0.73774 | μ (log location) | –0.87732 | *a* (scale) | 0.41173 |
| | σ (log scale) | 0.11191 | σ (log scale) | 0.14314 | *b* (shape) | 8.4917 |
| | Generalized Extreme Value (Pearson III) | | Weibull | | Weibull | |
| Kartepe | *k* (shape) | –0.293756 | | | | |
| | σ (scale) | 0.0839238 | *a* (scale) | 0.448754 | *a* (scale) | 0.44642 |
| | μ (location) | 0.480619 | *b* (shape) | 10.6939 | *b* (shape) | 8.5651 |
| | Generalized Extreme Value (Pearson III) | | Generalized Extreme Value (Pearson III) | | Weibull | |
| Körfez | *k* (shape) | –0.23626 | *k* (shape) | –0.34215 | | |
| | σ (scale) | 0.067217 | σ (scale) | 0.043029 | *a* (scale) | 0.42557 |
| | μ (location) | 0.49297 | μ (location) | 0.44343 | *b* (shape) | 6.8659 |
| | Generalized Extreme Value | | Weibull | | Generalized Extreme Value | |
| | (Pearson III) | | | | (Pearson III) | |
| Derince | *k* (shape) | –0.28642 | | | *k* (shape) | –0.39134 |
| | σ (scale) | 0.052886 | *a* (scale) | 0.40334 | σ (scale) | 0.054582 |
| | μ (location) | 0.40709 | *b* (shape) | 7.7756 | μ (location) | 0.37241 |
| | Generalized Extreme Value (Pearson III) | | Generalized Extreme Value (Pearson III) | | Extreme value Gumbel | |
| Karamürsel | *k* (shape) | –0.34745 | *k* (shape) | –0.28713 | | |
| | σ (scale) | 0.0533 | σ (scale) | 0.099085 | μ (location) | 0.46008 |
| | μ (location) | 0.49471 | μ (location) | 0.44859 | σ (scale) | 0.041224 |
| | Generalized Extreme Value (Pearson III) | | Generalized Extreme Value (Pearson III) | | Weibull | |
| Gebze | *k* (shape) | –0.5715 | *k* (shape) | –0.43182 | | |
| | σ (scale) | 0.085993 | σ (scale) | 0.044132 | *a* (scale) | 0.29844 |
| | μ (location) | 0.36784 | μ (location) | 0.2847 | *b* (shape) | 6.3425 |

NRWR model curves of the 12 districts in Kocaeli are available in Figs. 7–9, according to the three consecutive periods.

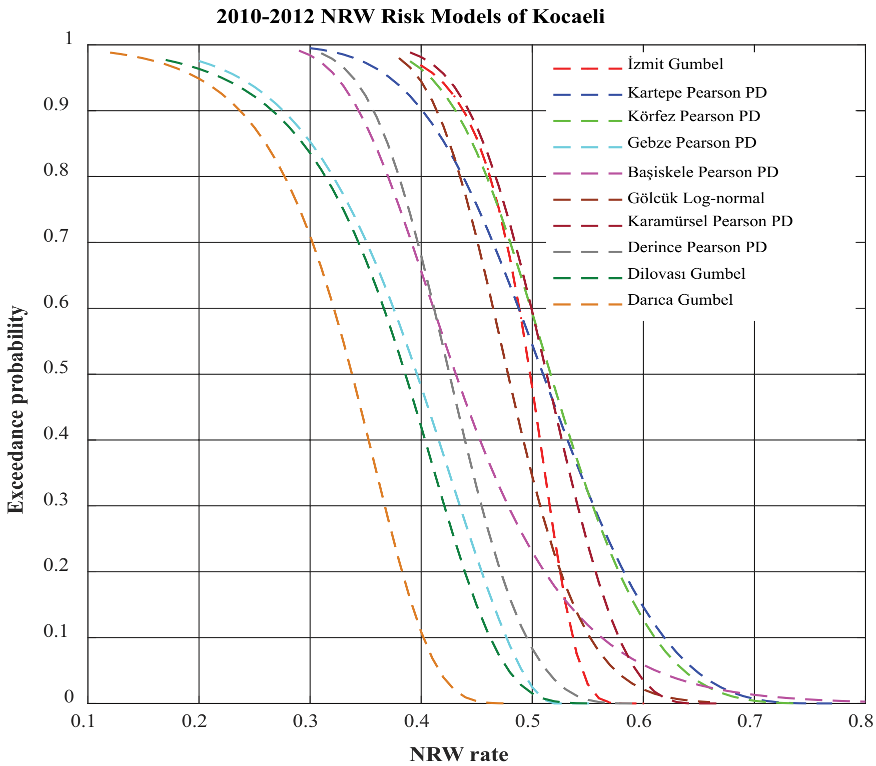


Fig. 7. The NRWR risk models of 12 districts in Kocaeli for the years 2010–2012.

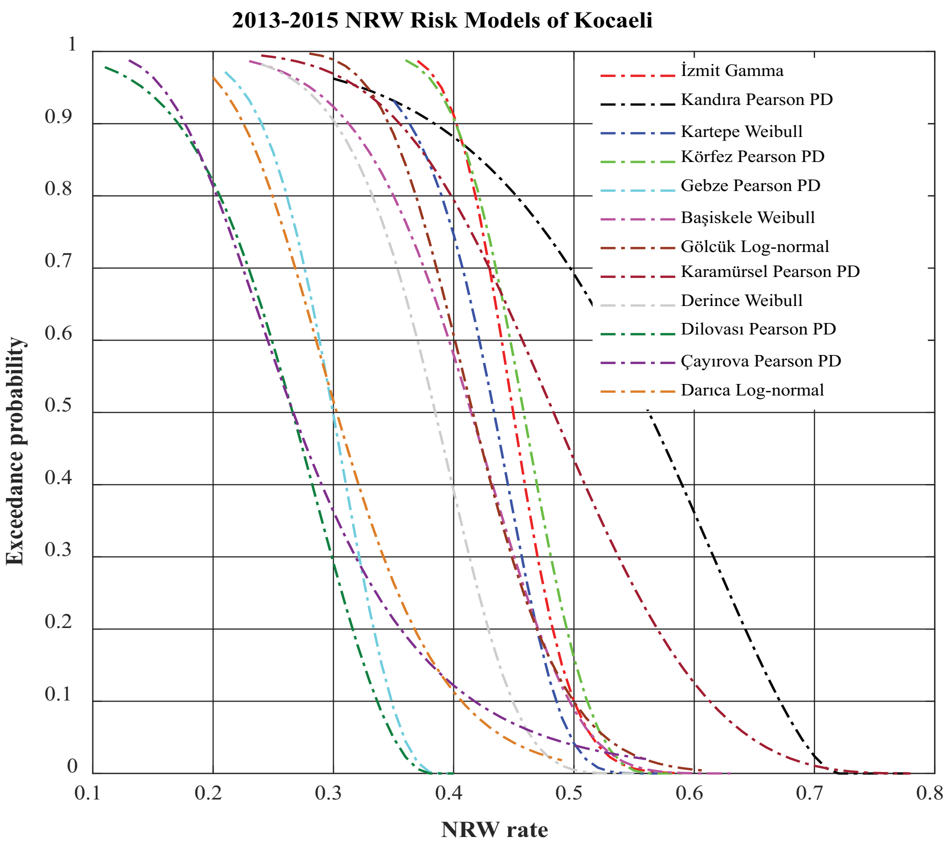


Fig. 8. NRWR risk models of 12 districts in Kocaeli for the years 2013–2015.

obvious performance change is occurred in Kandıra, according to Fig. 8. The performance results of each district have been discussed in detail through the performance charts suggested in this study, according to the average of the PDF model charts.

The latest period model curves are available in Fig. 9 for the years 2016–2018. In this period, Çayırova, Dilovası, Darıca, and Gebze are significantly better than the other eight districts in terms of the NRWR. On the other hand, Gölcük, Kartepe, and Körfez have the worst NRWR.

The performance evaluation of the 12 districts exceedance probability distribution model curves for average 50% risk value has been carried out in Figs. 10 and 11 with a new performance chart. The 1:1 or 45° straight line in the figures indicates that there is not any change in performances between the comparison years. The upper triangular area separated by a 1:1 straight-line indicates the performance deterioration while the lower triangle area points out the improvement of the NRWR performance for the comparison periods. The performances of 12 districts in Kocaeli have been analyzed according to the criteria determined by percentage lines in parallel with the 1:1 curve. The classification is as; 0%–10% very low, 10%–20% low performance, 20%–30% medium performance, 30%–40% high performance, >40% very high performance.

The NRWRs belonging to the 2010–2012, 2013–2015, and 2016–2018 years have been analyzed in detail through the suggested performance charts. It is seen that all district data is scattered within the lower triangular area (increasing performance) except Derince. Derince is just above the 1:1 straight-line and points out that the performance of this district for the 2016–2018 period is worse than the 2013–2015 period, according to Fig. 11.

Dilovası and Gebze have a very high performance during the 2013–2015 period, according to the 2010–2012 reference years. In the Kartepe district, the NRWR appears to be improved by over 30%. İzmit, Körfez, Gölcük, and Derince have a medium performance in the same periods. Karamürsel and Darıca remain at low-level performance. On the other hand, the Başiskele district has the lowest performance for the 2013–2015 period (Table 8).

The performance evaluation of the 12 districts in Kocaeli is available in Fig. 11 for the years 2016–2018. The best performance is in Kandıra for this period. This change may result from high investment, management, and meter replacing expenditures are available in Table 7 for the 2013–2015 and 2016–2018 time periods. In Kandıra, a significant investment has been made with a total of 25305 ($/km) between the 2016 and 2018 time period. In this period, the apparent losses that have an effect on the NRWR have been minimized

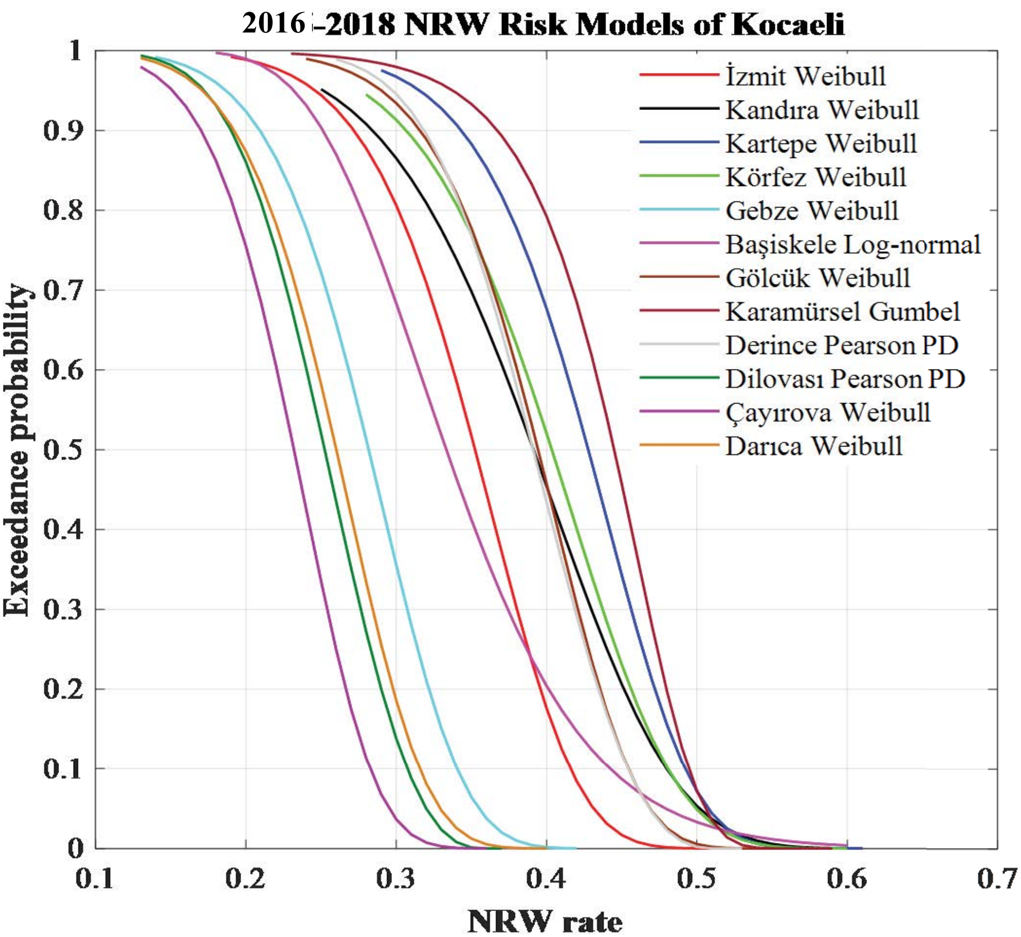


Fig. 9. NRWR risk models of 12 districts in Kocaeli for the 2016–2018 years.

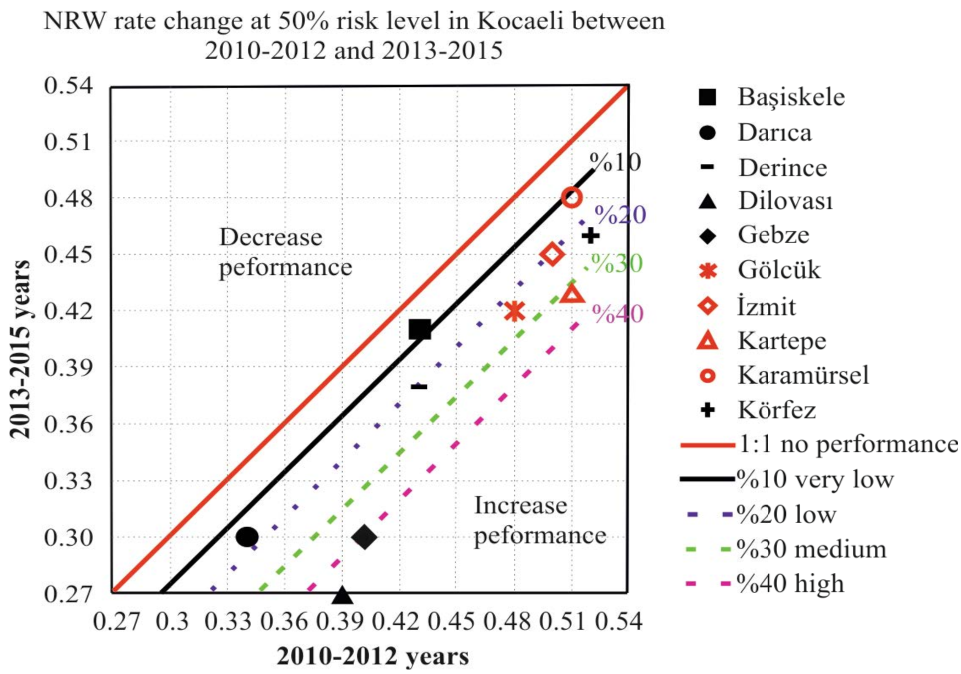


Fig. 10. Performances of 10 districts according to the NRWR for the 2013–2015 period.

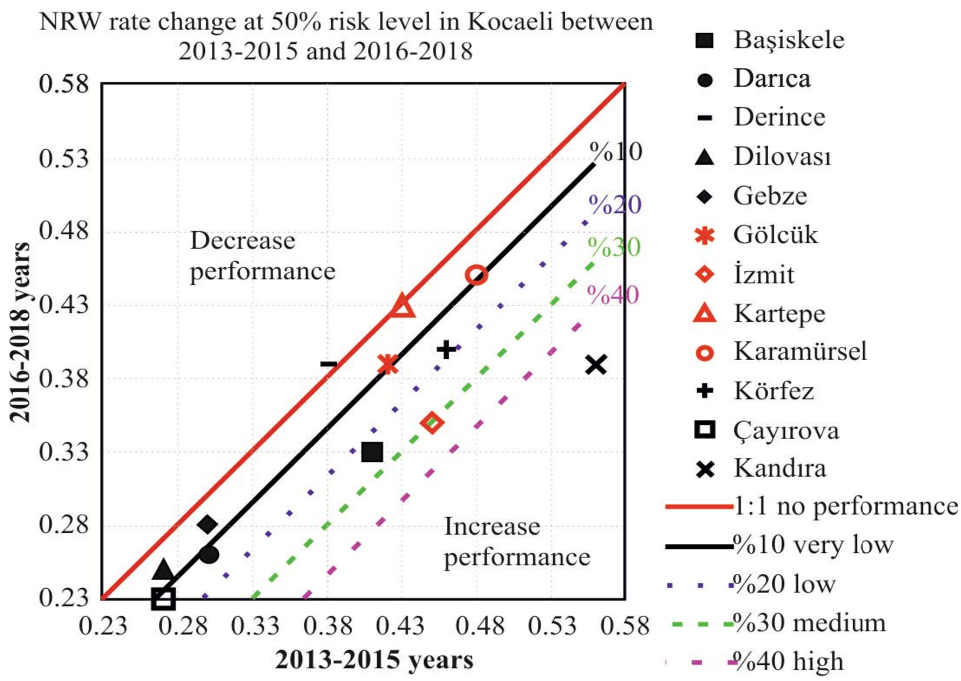


Fig. 11. Performances of 12 districts according to the NRW rate for the 2016–2018 period.

considerably by replacing the outworn meters in Kandıra. Through ten sections of district meter areas and two sections of pressure meter areas constructed in the county town, the real losses affecting the NRWR have been considerably minimized. The performance of Kandıra is higher than other districts in this period, however the NRWR is far behind many districts despite this. The reason is that only 7,244 km of the water supply network at the length of 1,600 km could be taken under control by isolating.

When analyzed the performance of the İzmit district, which has the highest number of water consumers in Kocaeli (İSU 2018), it is seen that there is approximately 20% improvement in the NRWR in the 2013–2015 time period in comparison to the 2010–2012 period given in

Fig. 10 and that the performance improvement is approximately 30% for the 2016–2018 time period in comparison to the 2013–2015 period given in Fig. 11. The most important reason for performance improvement is the hydraulic model studies that started in 2014 and are still continuing in the region. When Table 7 is analyzed in detail, it is seen that high investment expenditures, especially in the 2013–2015 and 2016–2018 time periods, help to reduce the NRWRs rapidly in these periods.

A considerable improvement in the NRWR performance has been also observed in Başiskele for the last period. Having looked at the budget used for the Başiskele district, it is seen that there are significant increases in both investment and management expenditures, especially in the 2013–2018 years. Başiskele follows hard on the heels of İzmit in terms of the total amount of expenditure in this period. Thirteen sections of DMAs have been installed in Başiskele within the framework of isolated zone studies and 12,338 km of the water supply network at the length of 854 km have been brought under control in this period. Active leakage control methods have been performed in DMAs and the failures have been repaired, and thus the real losses have been reduced. The replacement of outworn meters has continued at the same time to reduce apparent losses. It is planned to construct the PMAs in the region to ensure an ideal network pressure in order to reduce the NRWR in accordance with the desired levels. It is necessary to augment the DMAs and PMAs for better performance and lower NRWRs.

When analyzed the performance of the Körfez district according to performance charts in Figs. 10 and 11, it can be said that the NRW performance is respectively medium and low for the 2013–2015 and 2016–2018 time periods. As regards the expenditures given in Table 7, it is seen that the district budget for investment and management in the 2010–2012 period is not enough, but the total amount of investment and management expenditures in the 2013–2016 and 2016–2018 time periods is close to each other and the performance improvement is enough. The total water supply network length of the Körfez district is 680 km and 1,374 km of the network consists of asbestos pipe. The allocated budget has been used in recent years for replacing the outworn pipes that fail frequently. Meanwhile, meter changes have been carried out to reduce apparent losses. The expenditures made in the 2013–2015 time period are a little higher than the years 2016–2018, in consequence, the performance of 2013–2015 is somewhat better.

On the other hand, the performances of Çayırova and Darıca are close to the 10% comparison line. Karamürsel, Gebze, and Dilovası are just below 10% straight-line within the last period and it is evaluated as very low performance. Finally, there is not any significant change in Kartepe during the years 2016–2018.

The WDS infrastructure expenditures and the performances of all districts in Kocaeli city are available in Tables 7 and 8 in general for the 2010–2018 time period. In this section, the expenditures made for the water distribution infrastructures and the performance results have been evaluated together. In Başiskele, significant investments and management expenses have been made in the 2013–2018 period (total amount of expenditure: 35,547 ($/km)). A significant portion of the total amount belongs to the 2016–2018 period, this affects positively the performance of the above-mentioned district in the last period. A similarly low performance has continued in Darıca in the last two periods, therefore increasing investment and management expenditures is suggested to increase the performance. In Dilovası, the investment expenditures are low in the last period, so the performance has declined up to very low in the 2016–2018 period that was very high in the 2013–2015 period. A similar situation is also valid for the Gebze district. On the other hand, the infrastructure performance of the İzmit district has upgraded from low to medium due to increasing investment expenditures in three periods. The total expenditure is 34,002 ($/km) for the İzmit district, a significant amount for a permanent improvement. Especially, a significant water meter change expenditure ($/1 consumer) has been made in the İzmit and Kandıra districts between the 2016 and 2018 period. This expenditure affects positively the performances of these two districts in terms of the above-mentioned period. In the Kartepe district, the total investment

Table 7
Water distribution system infrastructure expenditures

| Expenditures | Investment expenditures ($/km) | | | Management expenditures ($/km) | | | Meter change ($/1 consumer) | | |
|---|---|---|---|---|---|---|---|---|---|
| Districts | 2010–2012 | 2013–2015 | 2016–2018 | 2010–2012 | 2013–2015 | 2016–2018 | 2010–2012 | 2013–2015 | 2016–2018 |
| Kandıra | 6,697 | 6,660 | 25,305 | 1,829 | 2,776 | 2,298 | 7 | 9 | 17 |
| İzmit | 7,775 | 8,483 | 9,065 | 3,803 | 3,580 | 1,296 | 3 | 6 | 17 |
| Başiskele | 122 | 12,899 | 13,169 | 2,532 | 2,788 | 4,037 | 4 | 6 | 5 |
| Körfez | 2,263 | 5,473 | 3,247 | 1,317 | 1,157 | 3,134 | 3 | 4 | 5 |
| Çayırova | 1,171 | 10,844 | 5,130 | 1,432 | 1,188 | 1,288 | 4 | 6 | 5 |
| Darıca | 0 | 1,357 | 2,022 | 470 | 933 | 1,732 | 4 | 4 | 9 |
| Gölcük | 533 | 8,942 | 3,468 | 4,197 | 1,732 | 1,415 | 3 | 4 | 14 |
| Karamürsel | 2,435 | 3,729 | 5,616 | 4,026 | 2,588 | 4,724 | 4 | 4 | 3 |
| Dilovası | 3,168 | 5,477 | 2,890 | 1,011 | 295 | 1,187 | 7 | 8 | 9 |
| Gebze | 1,637 | 9,523 | 1,506 | 4,121 | 1,202 | 2,238 | 3 | 3 | 10 |
| Kartepe | 7,174 | 14,710 | 4,100 | 3,730 | 1,840 | 1,786 | 3 | 6 | 8 |
| Derince | 5,003 | 6,252 | 4,965 | 1,083 | 1,013 | 929 | 3 | 6 | 5 |

Table 8
Performance results of the districts

| District | 2013–2015 based on 2010–2012 | 2016–2018 based on 2013–2015 | Performance change |
|---|---|---|---|
| Başiskele | Very low | Medium | Increase |
| Darıca | Low | Low | No change |
| Derince | Medium | No performance | Decrease |
| Dilovası | Very high | Very low | Decrease |
| Gebze | Very high | Very low | Decrease |
| Gölcük | Medium | Very low | Decrease |
| İzmit | Medium | High | Increase |
| Kartepe | High | Very low | Decrease |
| Karamürsel | Low | Very low | Decrease |
| Körfez | Medium | Low | Decrease |
| Kandıra | – | Very high | – |
| Çayırova | – | Low | – |

expenditure in the amount of 21,884 ($/km) made for the 2010–2012 and 2013–2015 years affects the 2013–2015 performance positively, and the NRWR performance has been determined as high according to the model results. It is seen in the last period that the district's performance is declined in parallel with the expenditures. In Kandıra, the total expenditure in the amount of 45,565 ($/km) between 2010 and 2018 is the most significant reason for very high performance in the last period.

Differently from the study of Kizilöz et al. [11], the district performances can be evaluated objectively using the performance charts given in this study. Infrastructure investment, management, and water meter change expenditures, which are the most significant indicators of the district performances, have been calculated for the analyzed periods and their relationships with the performances have been discussed. It is expected from water utilities to prioritize the NRWR investment planning and strategies through their comments and inferences on these quantitative indicators.

## 5. Conclusions

The NRWR performance evaluation has been made through the suggested performance analysis model for 12 districts for the 2010–2018 years. The water utilities of Kocaeli city have improved their NRWR performances in terms of investment, management, operation as well as maintenance activities. When the districts with high performance are analyzed, it is seen that certain activities such as district metered areas, pressure management, active leakage control method, and replacement of old network and water meters come to the forefront.

The practices preferred, expense items, and their amounts have differed in districts in accordance with the current situation of the infrastructure. It is recommended that the model analysis performances given in this study should be taken into account besides the implementation and management experience of each region for future planning to improve the NRWRs network more efficiently. A substantial amount should be put away for investments by referencing the expenditures made in the previous years to improve considerably the performance of many districts. Water utilities should evaluate their investments and the efficiency of their expenditures through a similar performance model analysis to monitor and improve their performances. In this study, the plans of Kocaeli city for the 25% NRWR target in 2023 have been reviewed by considering good practices that contribute significantly to the performance of each district. According to the model and analysis results, the DMA and PM activities should be prioritized in the other districts besides the Kandıra, Gebze, and İzmit districts to improve the NRWR performances more quickly.

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