Journal of Studies in Advanced Technologies
[İleri Teknolojilerde Çalışmalar Dergisi]
e-ISSN: 2980-2695

Research Article

Creation and Calibration of Hydraulic Model for Leakage Management in Water Distribution Systems

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Received: 22 October 2024; Accepted: 22 November 2024; Published: 31 December 2024

Abstract: Leaks occur at different rates in water distribution systems (WDSs). Network characteristics, high pressure, environmental factors and operational factors are effective on leaks. Field detection and monitoring activities should be implemented to reduce the volume of leaks resulting from faults in the WDS. The aim of this study is to create and calibrate the district metered area (DMA) based hydraulic model to understand the network behavior and monitor the hydraulic components. The hydraulic model is based on consumption data, network topology, characteristics and pipe roughness information. Calibration should be performed by comparing the pressures obtained from the model with the pressures measured in the field in order to apply the model in leakage management. Incomplete or incorrect network information may cause the difference between these two pressures to be large. In particular, basic data such as incomplete creation of the network topology, incomplete or incorrect acquisition of roughness and consumption information are effective in not providing model calibration. In the calibrated hydraulic model, it is possible to detect and prevent potential leaks by monitoring pressure changes at the nodes. It is thought that the results obtained in this study will constitute a reference in leakage management and hydraulic analysis.

Keywords: Distribution system, hydraulic model, model calibration, leakage management

Araştırma Makalesi

İçmesuyu Dağıtım Sistemlerinde Sızıntı Yönetimi için Hidrolik Modelin Oluşturulması ve Kalibrasyonu

Öz: İçmesuyu dağıtım sistemlerinde farklı oranlarda sızıntı meydana gelmektedir. Sızıntılar üzerinde şebeke özellikleri, yüksek basınç, çevresel faktörler ve işletme faktörleri etkilidir. Dağıtım sisteminde arızalardan kaynaklanan sızıntı hacminin azaltılması için sahada tespit ve izleme faaliyetleri uygulanmalıdır. Bu çalışmada, şebeke davranışının anlaşılması ve hidrolik bileşenlerin izlenmesi için İzole Ölçüm Bölge bazlı hidrolik modelin oluşturulması ve kalibrasyonu amaçlanmıştır. Hidrolik modelde, tüketim verileri, şebeke topolojik, karakteristik ve boru pürüzlülük bilgileri esas alınmaktadır. Modelin sızıntı yönetiminde uygulanabilmesi için modelden elde edilen basınçlar sahada ölçülen basınçlar ile kıyaslanarak kalibrasyon yapılmalıdır. Şebeke bilgilerinin eksik veya hatalı alınması bu iki basınç arasındaki farkın fazla olmasına neden olmaktadır. Model kalibrasyonunun sağlanmamasında özellikle, şebeke topolojisinin eksik oluşturulması, pürüzlülük ve tüketim bilgilerinin eksik veya yanlış alınması gibi temel veriler etkili olmaktadır. Kalibre edilmiş hidrolik modelde, düğüm noktalarında basınç değişimleri izlenerek potansiyel sızıntıların farkına varılması ve önlenmesi mümkün olmaktadır. Bu çalışmada elde edilen sonuçların sızıntı yönetiminde ve hidrolik analizinde referans oluşturacağı düşünülmektedir.

Anahtar Kelimeler: Dağıtım sistemi, hidrolik model, model kalibrasyonu, sızıntı yönetimi

Citation: F. Boztaş and M. Fırat, "Creation and Calibration of Hydraulic Model for Leakage Management in Water Distribution Systems", *Journal of Studies in Advanced Technologies*, vol. 2, no. 2, pp. 95-107, Dec 2024, doi: 10.63063/jsat.1571651

1. Introduction

Failures and leaks occurring due to various factors in WDSs cause the increasing the real loss volume which is a significant portion of volumetric water losses [1], [2]. To reduce these losses, water utilities must first determine how much loss is occurring, where and why the losses occur, and how they can be reduced [3]. Leaks in WDSs cause the reducing the water resources and increase pump operating durations, resulting in inefficient use of water and energy resources [4]. In addition, it creates a wide range of negative effects, such as increasing operating and maintenance costs due to increasing failure and leakage rates, decreasing service quality, increasing subscriber complaints, making the system technically inoperable, and changing water quality due to failure density [5], [6], [7], [8]. In the literature, various methods that are the pressure management, active leakage control, pipe material management, real-time monitoring etc., have been proposed at different times by various researchers and organizations (IWA, AWWA) in order to analyze the amount of leakage, recognize the leakage, detect and control leaks [9], [10]. Moreover, the studies of leakage estimation with support vector machine [11], leakage detection with transient-based matched-field (MFP) method [12], leakage analysis with BABE (burst and background estimates) method [13] have been applied. It can be said that they generally focus on one of the mentioned topics [14]. In recent years, mathematical-statistical and optimization-based methods have been applied to detect, prevent, control and manage leaks [15], [16], [17]. The most important difficulties or constraints in the implementation of such approaches can be shown as deficiencies or uncertainties in the information of the field data (network geometry, consumption data, pressure measurements, etc.) and difficulties in the calibration phase [18]. The study conducted by Boztaş [19] aimed to determine non-surface (unreported) leaks and a genetic algorithm-based optimization model was proposed. The proposed model in the study was tested in two distribution systems and the average accuracy rate was expressed as 92%.

Establishing the hydraulic model includes performing the hydraulic analysis by considering the existing conditions in the WDS (topology, diameter, material type, roughness coefficient, customer’s consumption characteristics, etc.) and monitoring the hydraulic parameters (e.g., flow and pressure) with field calibration [20]. In general, important issues which directly affect the model results, in the implementation of this model are the defining the flow rates at the nodes depending on the customer consumption characteristics, defining the existing network plan and characteristics, determining the pipe roughness’s to represent the real conditions [21]. After the hydraulic model is designed, field calibration is the most important step for its application in leakage management. Appropriate hydraulic models to be used to analyze a WDS require a calibration process [22]. The accuracy of the calibration process can be tested by comparing the data obtained from the hydraulic model and data measured in the field. Incomplete or incorrect network information results in a large difference between field data and model data. Uncertainties in the network topology and geometry, roughness and lack of consumption information are particularly effective in ensuring model calibration. In the hydraulic model calibrated with field data, it is possible to detect and prevent potential leaks by monitoring pressure changes at the nodes. Since the time required to detect and locate leaks that do not come to the surface will be reduced, the total leak volume in the system will also be reduced.

The aim of this study is to create and calibrate the district metered area (DMA) based hydraulic model to understand the network behavior and monitor the hydraulic components. The hydraulic model is based on consumption data, network topology, characteristics and pipe roughness information. For this purpose, a hydraulic model was created for the pilot isolated region. The pressures obtained from the model were compared with the pressures measured in the field and calibration was performed in order to apply the model in leakage management. The most important advantage of this study is the use of real field data. Creating hydraulic model calibration is performed according to these data. In real field problems, model and calibration processes are time-consuming and costly depending on the accuracy of network and customer information. This study also reveals the effect of field data accuracy on model calibration. In this respect, it makes a significant contribution to researchers.

2. Material and Method

2.1. Hydraulic Model and Calibration

A model, in its most basic definition, is a simplification, in other words, a simulation, of a real-world event or system. Hydraulic modeling is the process of analyzing the hydraulic behavior of the infrastructure systems (water, sewage, drainage and flood) in the field and creating a mathematical model of the system [19]. Hydraulic models do not fully reflect the field behavior of the real systems they simulate mathematically due to uncertainties in the input data (network geometry, pipe characteristics, consumption quantities, etc.), and a difference occurs between them. At this point, the concept of calibration which is basically the process of minimizing the differences between a model and the system it represents, comes into play. The main parameters that cause this difference between the model and the field are the network geometry, time-dependent changes in network characteristics, uncertainties in consumption and leakages [19]. The study area is the Akpınar DMA located in Malatya province in southeastern Turkey (Figure 1). The EPANET program for hydraulic modeling and calibration was used. Hazen-William's formula was considered for hydraulic calculations. The QGIS software which is opensource software, were used to make the data suitable for modeling. The data required in the hydraulic model preparation process for the Akpınar DMA region is summarized below.

Figure 1. Study area and Akpınar DMA [19]

2.2. Network Topology

It is necessary to have the geometry of that network in a digital environment, since the hydraulic model of a water network means simulating the hydraulic properties of that network in a digital environment. The network in the Akpınar DMA is an older network than the average in Malatya province (Figure 2). It has a fragmented network structure obtained by combining productions completed at different times. The network age varies between 30 and 40 years.

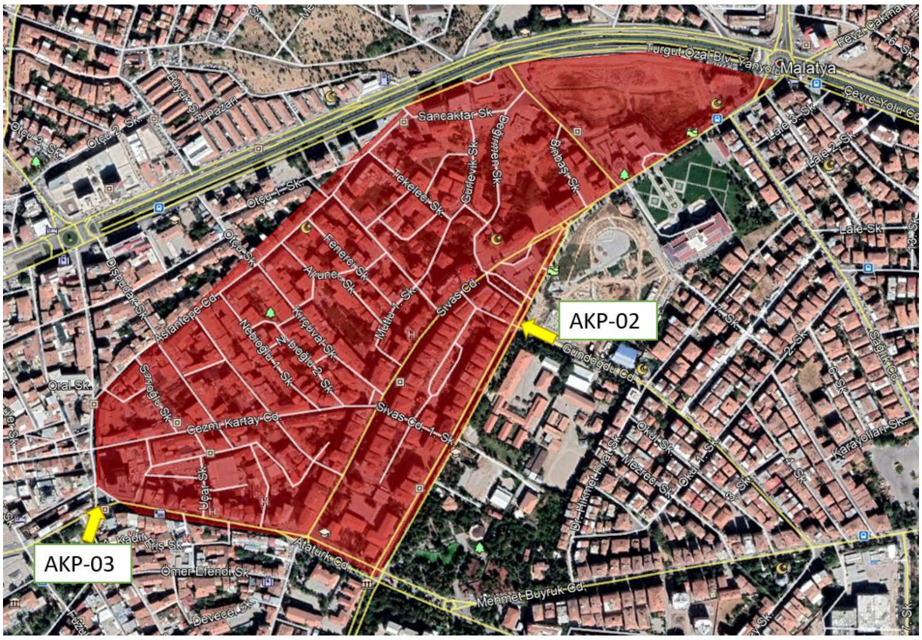

Figure 2. Akpınar DMA network layout [19]

The data regarding the network geometry are only digital operation plans consisting of 40-year-old maps available on paper. These data were transferred to the digital environment by Malatya Water and Sewerage Administration (MASKİ) and as the faults that occurred over time were intervened, the verifications and updates of the existing digital map were carried out with the measurements taken from the network that was opened. However, the data available is not completely reliable. The network generally consists of, Ductile Font (DF), Polyvinyl Chloride (PVC) and Asbestos Cement Pipe (ACP) pipes with ages ranging from 30 to 40 (Table 1).

Table 1. Akpınar DMA Network Information

Diameter (mm)	Pipe material	Length (m)
Ø400	ACP	270.24
Ø300	ACP	184.02
Ø175	ACP	474.50
Ø150	ACP	1447.39
Ø150	DF	210.61
Ø100	DF	261.23
Ø140	PVC	133.93
Ø125	PVC	938.30
Ø110	PVC	9544.00

Water supply to Akpınar DMA is provided by DN 900 mm steel pipe from İnderesi Water Reservoir. While the lower level of the reservoir is 1038.51 m, the upper level of the reservoir is 1042.21 m. The topology of Akpınar DMA was obtained by means of current maps and digital terrain model maps. QGIS program was used to transfer the data to EPANET hydraulic model. The water consumptions were obtained from MASKİ in order to determine the consumption characteristics of the DMA. Total number of customers is 2230 and the daily water consumption per customer is 0.416 m3/day/customer. The average daily consumption is 927.2575 m3/day (Table 2). Network specific consumption patterns were obtained using existing flow measurements of the study area. The consumption in patterns is modeled according to the obtained consumption patterns (Figure 3). Although measurements of hydraulic events occurring in the field (pressure, flow) are not directly essential for the hydraulic model, they are necessary for model validation and calibration.

Table 2. The customer data in DMA

Customer type	Number of customers	Daily consumption (m^3/day)	Daily consumption per customer (m^3/day/customer)
Residential	1842	712.11	0.387
Construction	1	0.19	0.188
Public	9	30.54	3.393
Commercial	373	121.28	0.325
Total	2230	927.2575	0.416

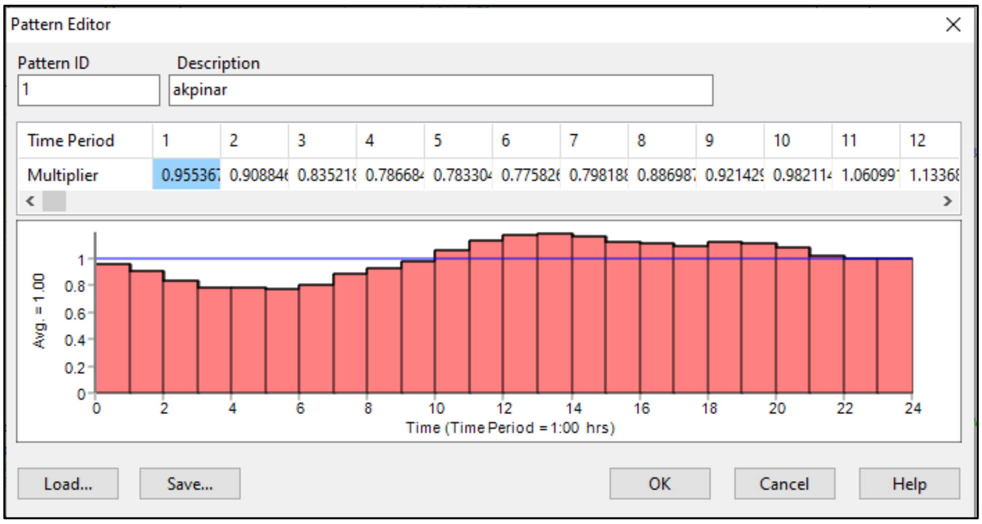

Figure 3. Study area consumption pattern obtained as a result of flow monitoring [19]

The flow measurement data obtained from the AKP-02 measurement point are as shown in Figure 4. The flow rate from the measurement point to the working area fluctuates between 11 l/s and 21 l/s depending on consumption fluctuations during the day. The data obtained within the scope of the study were compiled in the EPANET environment and hydraulic simulations were completed (Figure 5). The next stage is the calibration stage. It is aimed to minimize the differences by comparing the calculated data with the measured values.

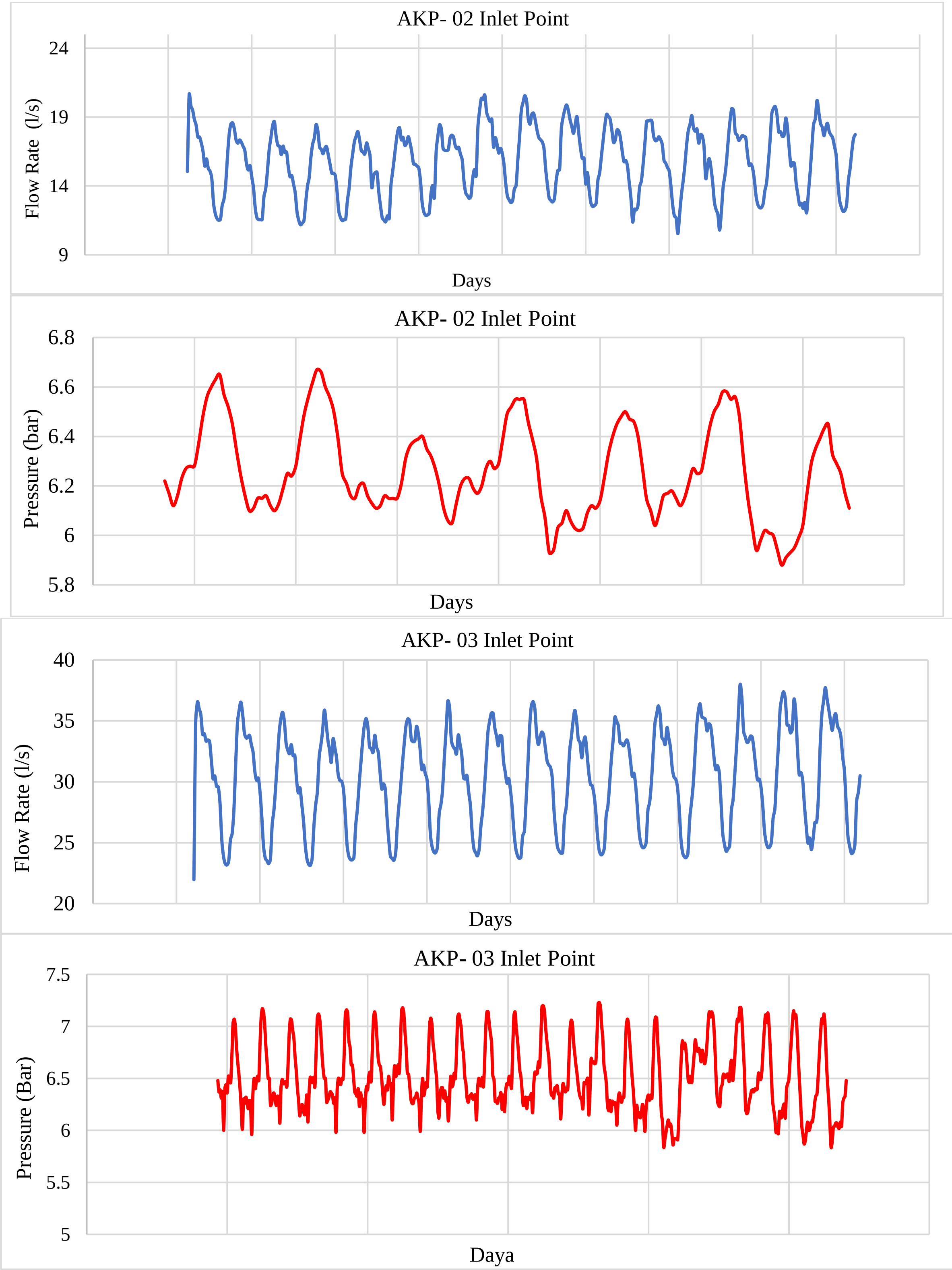

Figure 4. Flow and pressure changes in the application area [19]

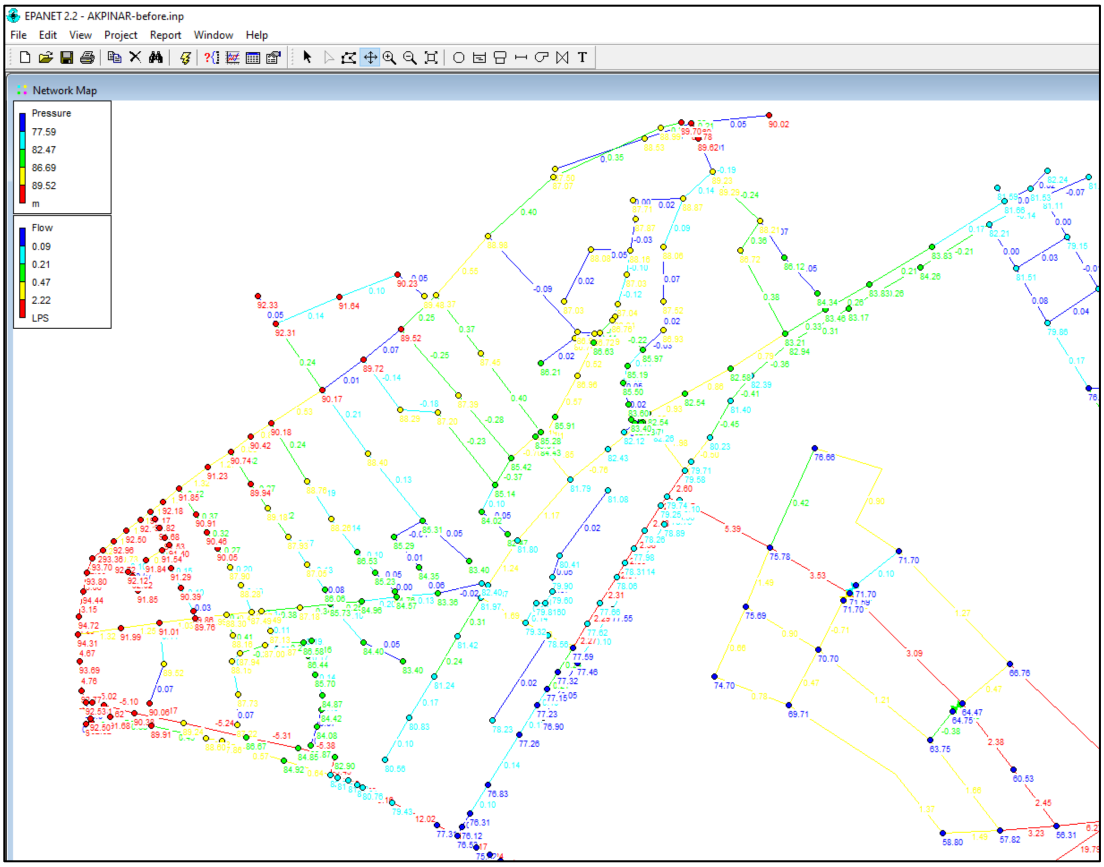

Figure 5. Hydraulic model of Akpınar DMA [19]

2.3. Model Calibration

In the EPANET software, calibration data can be made in response to the pressure data measured in the field at the nodes, and in response to the flow rate (velocity, flow) data measured in the field at the pipes. The network elements were selected that represented the measurement points available in the field on the hydraulic model in order to complete the calibration of the network where hydraulic model was created. In this context, the flow meter data at the AKP-02 and AKP-03 points were considered for the inlet flow rate. Additionally, Node23 and Node250 nodes were determined for pressure calibration in the model. Link_Pipe611 and Link_Pipe751 were selected for velocity calibration. The field measurement data of the network elements in question, representing the measurement points in the model, were defined in the program using the calibration interface of the EPANET program for the pipes numbered 611 and 751 and the nodes numbered 23 and 250. Pressure and flow data for measurement points were compared using the EPANET calibration feature. The red line in the graphs shows the model results, and the green dots show the field measurements.

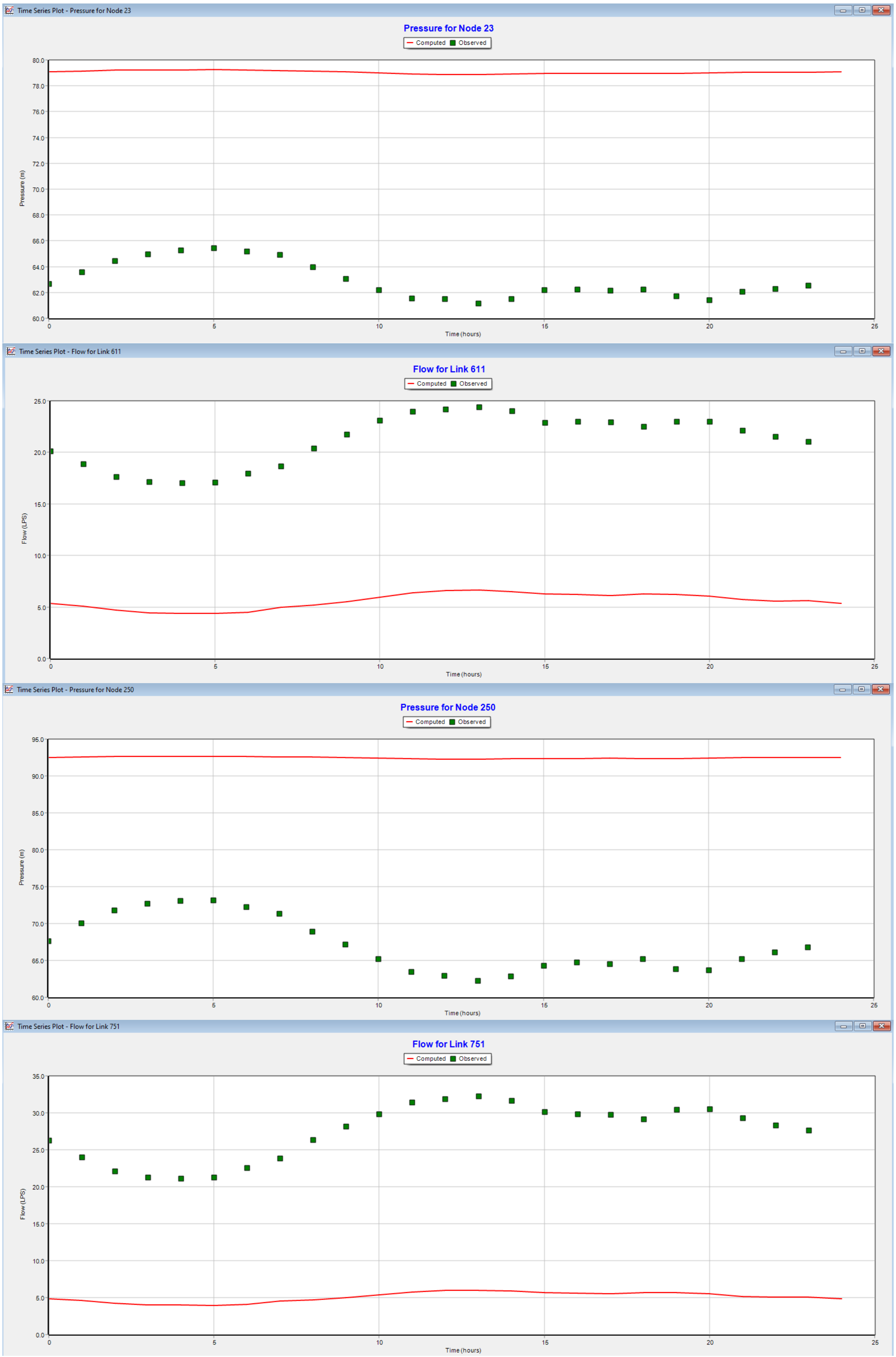

Figure 6. Field and model comparison for flow and pressure data at the nodes determined in the model.

Since the field measurements consist of data taken hourly, their reflection on the graph is in the form of points. It is observed that the pressure data calculated for node 23 in the model is higher than the pressure data measured in the field and the time-dependent change trends do not overlap. The designed hydraulic model is far from reflecting the field results at this stage. It is seen that the flow rates calculated for pipe no. 611 in the hydraulic model are below the flow rates measured in the field. Moreover, it is seen that the pressure values calculated for node 250 are higher than the measured pressures and their trends do not overlap. The calculated flow rates for pipe number 751 in the hydraulic model were below the measured flow rates, similar to those at the other measurement points. Calibration statistics for the pressure parameter of the regional hydraulic model are as shown in Table 3. In hydraulic model calibration, the results obtained from the model at the node point must be close to the field measurement results. The reduction of the difference between this model and the field results increases the potential of the model to represent the field. Therefore, it is essential to determine the model parameters correctly to reduce the difference.

There is no clear correlation between the flow data of the hydraulic model and the field measurements. It turned out that the hydraulic model did not represent the field conditions. Therefore, the network data needs to be corrected. An attempt was made to correct missing or incorrect data such as pipe roughness coefficients, network geometry, consumption distribution, and leaks. The inflow rates passing through the customer meters in the region were compared. In the region, $Q_{consumer}$ = (927.2575 m^3/day * 1000 l/m^3)/86400 s/day and $Q_{consumer}$ = 10.73 l/s were obtained. As a result, it can be roughly said that there is a loss flow rate of 36.15 l/s in DMA. This corresponds to a loss rate of approximately 77%.

Table 3. Calibration statistics for pressure and flow in DMA

Location	Number of Measurement	Average of Measurements	Average of Calculations	Average Error	Root Mean Square Error (RMSE)
Pressure					
Node 23	24	62.94	79.06	16.114	16.165
Node 250	24	67.08	92.48	25.395	25.628
Network	48	65.01	85.77	20.755	21.425
Flow Rate					
Node 611	24	21.19	5.62	15.571	15.666
Node 751	24	27.47	5.08	22.391	22.593
Network	48	24.33	5.35	18.981	19.440

The widely used minimum night flow analysis method was applied to estimate the leakage flow rate in the region. The average of daily minimum flow rates at AKP-02 point is 11.3 l/s and at AKP-03 point is 23.8 l/s. The average of the minimum flow rates passing through both flow meters is 35.1 l/s. In the study conducted by Boztaş et al. [23], it was stated that there was a loss of approximately 75% in the region according to the minimum night flow analysis. The leakage flow rate calculated in the calibration was distributed to the nodes in the hydraulic model, considering the required flow rates and pipe lengths. The network in DMA consists mainly of PVC and ACP pipes. The Hazen-Williams coefficient was initially selected as 150 for PVC and 130 for ACP. During the calibration phase, systematic hydraulic analysis was performed, improvements were monitored and finally coefficient was selected as130 for PVC and 110 for ACP. After the hydraulic model for the DMA was completed, the first stage calibration values were calculated according to the field data. According to the results, the roughness coefficient for network pipes has been updated and network topology was revised. Moreover, the leakage flow rate was calculated and distributed to the nodes in proportion to their consumption. The leakage distribution needs to be investigated realistically with further studies, and the leakage model of the region needs to be determined in order to create a calibration model that is more realistic and more consistent with field measurements. Once the hydraulic model is created and calibrated, as long as this model is kept dynamic, it will be possible to quickly detect and intervene in new leaks.

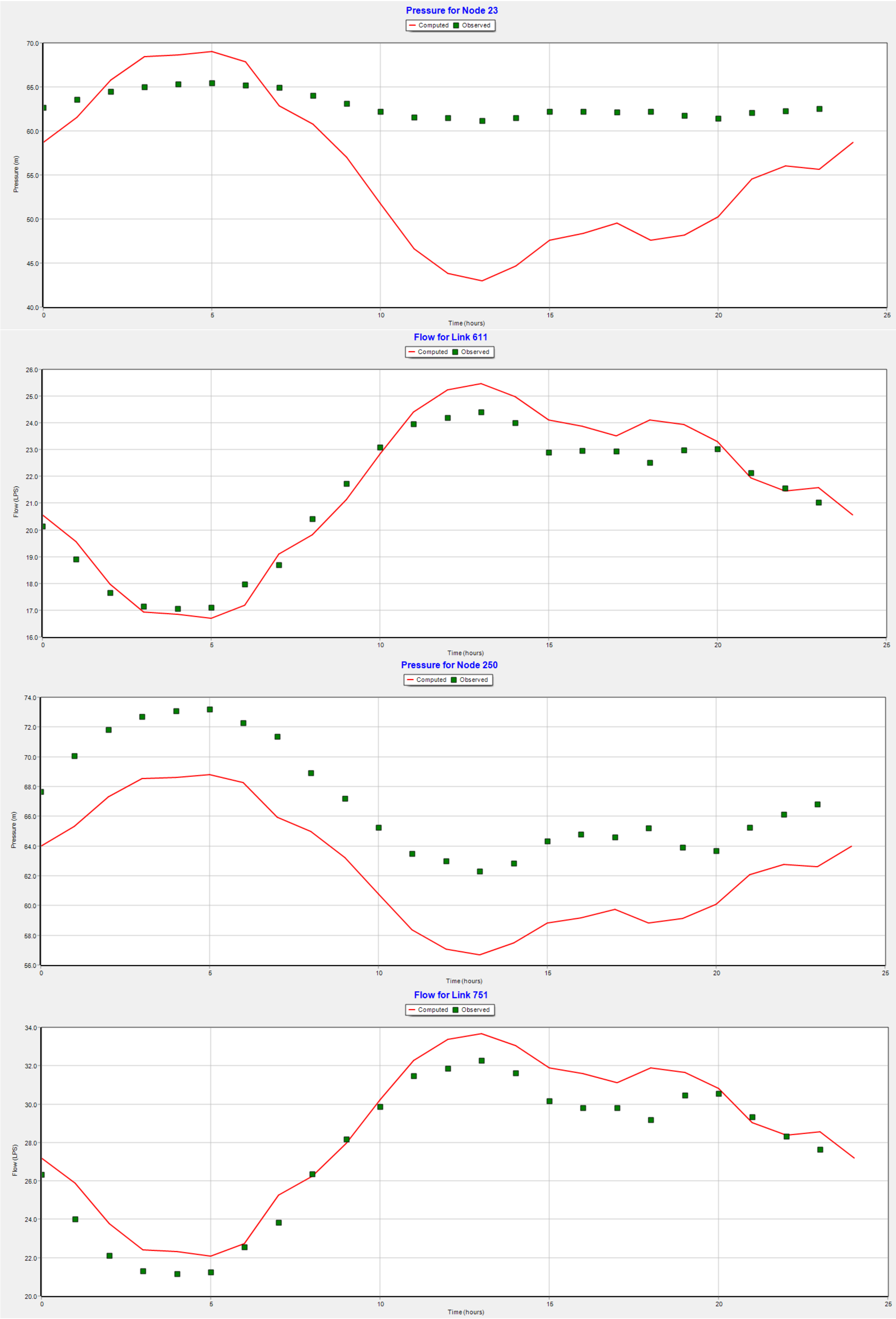

Figure 7. Comparison of field and model for flow and pressure data at nodes after calibration.

Data obtained from the field measurements and the calibrated hydraulic model for pipe No. 611 were compared. A visible agreement between the trends of the data and the differences between the field measurements and the model results are largely closed. Another node where the measurement points in the field are represented on the model is node number 250. After the calibration studies, the differences between the field measurements and the model results have decreased but have not completely closed. However, the trends of the two data sets overlap with each other. The differences between the field and the model for pipe no. 751 are closed and the data sets are compatible with each other (Table 4).

Table 4. Calibration statistics for pressure and flow in DMA

Location	Number of Measurement	Average of Measurements	Average of Calculations	Average Error	RMSE
Pressure					
Node 23	24	62.94	55.35	8.785	10.415
Node 250	24	67.08	62.44	4.641	4.713
Network	48	65.01	58.90	6.713	8.083
Flow Rate					
Node 611	24	21.19	21.52	0.612	0.716
Node 751	24	27.47	28.48	1.053	1.248
Network	48	24.33	25.00	0.833	1.017

When the post-calibration correlation graph for the pressure data is examined, two data sets are much more compatible with each other than before calibration, although a high-degree linear relationship between the field and the model has not been fully established. A high degree of agreement was achieved between the field and model results, and the differences between the two were reduced to very small amounts.

3. Results

After the hydraulic model for the Akpınar region was completed, the first stage calibration values were calculated based on the field data. The roughness coefficient for network pipes was updated. Inaccuracies detected in the network geometry were corrected. The leakage flow rate is distributed by taking into account the consumption at the nodes and in proportion to the pipe lengths. In order to create a calibration model that is more realistic and more consistent with field measurements, the leakage distribution needs to be investigated realistically and the leakage model of the region needs to be determined. The most fundamental problem for hydraulic model and calibration is to provide reliable and accurate data in the field. In particular, network topology, pipe roughness and accuracy of water consumption directly affect model calibration. In the studies conducted in the pilot region, it was determined that the model calibration was improved as a result of updating these data with field studies. The network hydraulic model provides important information for technical personnel about the behavior of the system. It is possible to monitor and prevent new leaks by using the network hydraulic model. In future studies, it is recommended to create a leak management and monitoring system based on the hydraulic model. It will also be possible to monitor excessive or unregistered subscriber consumption in the system

Author Contributions

Methodology, M.F.; software, F.B.; validation, F.B.; investigation, M.F. and F.B.; writing and editing, M.F.; visualization and design, M.F. All authors have read and approved the published version of the manuscript.

Acknowledgments

This study was supported by Inonu University Scientific Research Project Unit (IUBAP- FDK-2020-2054).

Conflicts of Interest

The authors declare no conflict of interest.

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