Assessing the failures in water distribution networks using a combination of geographic information system, EPANET 2, and descriptive statistical analysis: a case study

Assessing the failures in water distribution networks using a combination of Geographic Information System, EPANET 2, and descriptive statistical analysis: A case study

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Abstract

Nowadays, issues related water are considered one of the most significant and vital problems in human societies. One of the fundamental branches of the water crisis is the distribution network-related problems. The present study attempted to extract, classify and verify the failure data obtained from the Preventive Maintenance database of Birjand Water Distribution Network (WDN). The WDN was meshed in terms of the rate of failures using a combination of Geographic Information Systems (GIS) and EPANET 2. Then it was assessed by using the descriptive statistical analysis method. Investigations revealed that the middle sections of WDN involved the highest rate of failures. Furthermore, the investigations demonstrated that from 2011 to 2016 the highest rate of failures per kilometer per year ranged in range of 0.6 to 1.8 which involved the highest aggregation for all cells. In this regard, the highest intensity aggregation of occurrence rate in 2011 was estimated as 1.4 to 1.8, while in 2012, 2013, and 2016 it was estimated as 1-1.4 and finally in 2014 and 2015, estimations showed an interval of 0.6-1.

Keywords: failure rate; water distribution network; geographic information system; descriptive statistics

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1- Introduction

Every day, more than 50 thousand people die due to inaccessibility to clean water all over the world. According to the Falkenmark index, a typical condition is defined as having access to more than 1700 m^3 of clean water annually per person in any region; if this number falls between 1000 to 1700 m^3, the area will face water stress, and if the amount of safe water per capita reduces to less than 1000 m^3, it is considered as a water crisis (Kaczan and Ward, 2011). Predictions made by the Food and Agriculture Organization (FAO) shows that up until 2025, almost 1.9 billion people all over the world will face absolute water scarcity, and 2 out of 3 people will be subject to water stress conditions (Alavian et al., 2009). The results of these statistics denote the sensitivity of water resources shortages as well as the necessity of adequate, seamless, and efficient management of the existing resources.

Water undergoes expensive treatment processes at the purification plant before entering the distribution network. While, if failures happen in the water network, in addition to the loss of water, the economic costs spent on water treatment will be wasted (Romano, Kapelan, & Savić, 2013; Shi, Zhang, & Ho, 2013). The corrosion and exhaustion of distribution networks and pressure differences in pipes (due to changes of demands during daily cycles) can be included as the causes of failures in water distribution networks (WDNs) (Mahmoodian and Aryai, 2017). Therefore, balancing the pressure as well as managing modifications and renovations of networks could contribute to the reduction of losses in water resources and optimization of economic costs. Yi Wu and Sage (2006) presented a model to assess pipes' failure points and optimize present failures in the network. In this study, pressure calibration was used to reduce the number of failures by minimizing the distance between actual and simulated pressure values (Wu and Sage, 2008). Lee et al. (2011) offered a model for identification, early warning, and leakage control of the pipeline within Beijing's drinkable WDN. The model was designed based on geographical information, and it was capable of estimating the possibility of leakage in any region within the pipeline by using its history. The purpose of designing and implementing such a model was to quickly identify leakage in WDNs (Li et al., 2011). Xu et al. (2013) studied a part of Beijing WDN in regarding failure rates in the pipes from 2008 until 2011. Using the Genetic Algorithm, this study presented a model for fast identification of failure occurrence area and an economic replacement for damaged pipes (in the shortest time possible). The outcomes of the study by Xu et al. offered the possibility for a quick replacement of damaged pipes with the emphasis on economic constraints (Xu, Chen, Ma, & Blanckaert, 2013). In a study by Okeya et al. (2014), a burst detection methodology was used. This methodology utilized distributed real-time sensor data, a data assimilation method, and a hydraulic model. The model was assessed and analysed to evaluate the performance of various burst detection metrics under different conditions (I Okeya, Kapelan, Hutton, & Naga, 2014). In another study, Jung and Lansey (2014) used the artificial neural network and statistical process control in order to identify failures in WDNs. Given the performance tolerance of pipes, valves and also their effects on the responses of the prediction problem, a nonlinear Kalman filter was used to mitigate modelling noises (Jung and Lansey, 2014). Laucelli and Meniconi (2015) conducted a set of studies on Germanopoulos leak detection method. The model was developed according to experimental observations by assuming a linear elastic behaviour in the pipes. In this study, modelling on the leak detection problem was discussed and compared through different views (Laucelli and Meniconi, 2015). In another study by Okeya et al. (2015), online failure positioning in urban WDNs was investigated. This study attempted to compare the consumed flow rate values and the residual pressure in network nodes through both the real and simulated values of the barometer and flow meter systems. Then, in order to increase the accuracy of detections, the difference between hydraulic prediction quantities (online) and the real values were optimized by using heuristic algorithms. The results of this study showed that the detections and predictions made by the hydraulic model involved a high efficiency for controlling pipe failures as well as preventing leakage (Isaac Okeya, Hutton, & Kapelan, 2015). Giustolisi (2016) conducted a set of studies on improving the hydraulic model of urban WDN and detecting leakage and failure points in the network. In order to plan and manage water distribution in the supply network, the WDNetXL software was used. In this study, the hydraulic features and network topology were analysed by indicating leakage control modules (Giustolisi, 2016).

The purpose of the present study also includes: (i) providing a complete database comprising the present failures in Birjand WDN through a combination of Preventive Maintenance (PM), Geographic Information Systems (GIS) and EPANET 2 qualitative-hydraulic processor, and (ii) analysing the created zones by using a meshing system of the failure rate in each cell.

2- Material and Method

The present study was conducted on Birjand city, the capital of Southern Khorasan province, which is located in a region with a dry and semi-arid climate. The city is situated at elevation 1470 meters above sea level with a longitude of 59° 13' and latitude of 32° 53', occupying a total area of 28 km^2 with a total population of more than 178000 people. The average annual maximum and minimum temperature in Birjand is reported as 28 and 8 degrees, respectively. According to Iran Meteorological Organization, the greatest extent of rainfall has been recorded between December and May, with an average of 171 mm per year. No permanent rivers are surrounding this city which only includes majorly seasonal waterways and streams. Consequently, the water supply for the city is provided through 34 wells located in four plains around the city with a flow rate of 950 Litres per second. Birjand is the first city of Iran in which an organized water distribution is in operation (Birjand's Ablole water pipe agency), and it is also the second city in history to be equipped with an urban water distribution network in 1923 (Shahryari et al., 2011). The WDN in Birjand provides services for 70000 users, which, as demonstrated in Figure 1, are divided into seven zones (pressure zones).

The present study was conducted with a focus on statistical, geographic, and hydraulic analysis of failures in Birjand WDN which was carried out in four general steps.

2-1- Providing a database of failures in water distribution network

In the first step of this study, the entire failures of Birjand water distribution from 2011 to 2016 were extracted, classified, and verified using the archive, which entailed recorded reports by Birjand Water and Wastewater Company. Given the probability of errors in the recordings of data related to failures in WDN, the entire extracted information was verified by using engineering judgment. To this end, the obtained statistical information was analysed twice through brainstorming and during which the erroneous data were not regarded as evaluation criteria. Brainstorming is an approach for collective decision making employed to produce a large number of ideas for a problem or subject (Osborn, 1953). This approach was first presented by Alex F. Osborn in 1939 and became practical for scientific analyses.

In present study, all data are gathered from water and wastewater company of Birjand City and they are related to field data gathering and archives. Pressure amounts are measured by online barometers in WDN and also, flow values are detected by flowmeters. Likewise, the diameters, location of facilities and dimension of pipes are collected from design documents from historical information. All collected data are proved by experts in water and wastewater company of Birjand City. The data are related to 2011-2016 because of the reengineering time in the WDN. In 2011, the mentioned WDN is reengineered and the hydraulic pattern of it is constant from 2011 till 2016. Likewise, the online Supervisory Control and Data Acquisition (SCADA) boards data should be calibrated in WDN and the last time of data validation is connected to 2016 and therefore, duration of 2011-2016 is available valid data for decision making and modelling. From

2016 till 2021, the WDN is reengineered and the declared process is continued.

2-2- Linking the extracted data of failures in Preventive Maintenance System

The extracted data from failures after verification and classification were entered into the PM system database of Birjand water distribution. The PM system is a coherent database in which the details of failures in urban water distribution such as the failure cause, incident magnitude, and location of failures are recorded online and offline (Yang, Ma, Peng, Zhai, & Zhao, 2017). In this study, the entire data of failures taken place were classified in the PM system based on the date, cause, and location of the incident. The purpose of providing such a database is the ability to update failures online.

2-3- Meshing the water distribution network

To perform a risk analysis of failures, the incident data of WDN were entered into the GIS. Next, the failures data of WDN (PM data), GIS, and EPANET 2 network hydraulic software were integrated for decision making and managing the failures (Brown, 2004; Dandy and Engelhardt, 2001; Eljamassi and Abeaid, 2013; Kao and Li, 2007; Kim, Inakazu, Koizumi, & Koo, 2013; Shamsi, 2005). The aggregation of failures in Birjand WDN from 2011 to 2016 is demonstrated in Figure 2.

In the following, it must be mentioned that for the meshing of Birjand WDN, a set of cells was created in ArcGIS 10.2 software. Since the dimension of meshes must be adequate for zoning failures in the WDN, initial tests were carried out in ArcGIS, and the dimension of 500m × 500m was selected. Furthermore, the values of failure rate in pipes were calculated based on equation (1) and then layered in the aforementioned meshes.

(1)

$$\text{Rate Of Occurrence (Occurrences per Km)} = \frac{\text{Number of occurence in each cell}}{\text{Sum of pipes lenghth in each cell (Km)}}$$

2-4- Descriptive statistical analysis of failures

Descriptive statistical analysis on the rate of failures in the pipelines of Birjand WDN for the time interval of 2011-2016 was conducted. The purpose of these analyses was to examine the rhythm of changes concerning the occurrence of failure in WDN in a 5-year interval and to assess the management system and modify the network in the desired region. It must be mentioned that the calculations of descriptive statistical analysis were carried out by using Excel 2013 and SPSS 17 software (de Oliveira, Neill, Garrett Jr, & Soibelman, 2010; Mudholkar and Srivastava, 1993; Xie and Sun, 2009; Zhang and Gockenbach, 2007).

3- Results and Discussion

Before all description, it is worth noting that the case study of present research is located in dry climate and the failure can be caused by sudden drop in water table or failures in well operations. Also, the mentioned water resources (34 wells around the city) are not filled by sequential precipitation. Also, the declared fact may be effective on the leakage and water stress. But, In the present study, WDN’s operation aspects are evaluated and some other issues may be interfering in the outcomes of this investigation.

The results of calculations regarding the rate of failures and their meshing in GIS layers for a time interval of 2011-2016 are presented in Figure 3.

The results of descriptive statistical analysis of Birjand WDN from 2011 to 2016 are presented in Table 1.

As can be seen in Figure 3(a) and Table 1, it is understood that the maximum and minimum rates of failure in 2011 were 16.76 and 0.13, respectively. Meanwhile, the mean and skewness of failure rate in 2011 were estimated to be 1.73 and 4.75, respectively. Through analysing mean and positive skewness values of failure rate data in 2011, it can be concluded that the aggregation of failure data was inclined towards the minimum values. Also, according to Figure 4, the maximum rates of failures were in a range of 1.4-1.8. It should be pointed out that in this study, the rates of failures more than seven $(\mathit{Failure}\ \text{Rate} \geq 7)$ were considered as a crisis situation. The critical failures of 2011 in the cell range of 33 to 54 in Figure 3(a) have had the highest aggregation, In terms of location. These points are located within the central areas of the Birjand WDN map.

The analysis of Figure 3(b) demonstrates the fact that the failures in 2012 in the entire cells in Birjand WDN involve a rate of failure between 0.15 and 11.68. As can also be seen in Table 1, a mean and skewness of 2.16 and 2.03 were calculated, respectively, for the rate of failures in 2012. This shows that the normal distribution of data is inclined toward minimum values, but the intensity of such inclination was less than 2011. As presented in Figure 5, the highest rate of failures in 2012 was aggregated in a range of 1-1.4. By comparing Figure 3(b) to Figure 3(a), it is clear that the rate of failures in 2012 (aggregation in cells 33 to 100) compared to 2011 became more intensified toward the Southern regions of Birjand.

The analysis of Figure 3(c) and Table 1 show that the rate of failures in 2013 with a minimum, maximum, mean and skewness of 0.17, 14.96, 2.23 and 2.68, respectively, is similar to 2012. Furthermore, by comparing Figure 3(c) to Figure 3(b), the similarity between the distribution of failures' place in terms of intensity in 2012 and 2013 can be determined. Meanwhile, according to Figure 6, it can be interpreted that the highest rate of failures in 2013 was taken place in the range of 1-1.4, similar to 2012.

As demonstrated in Figure 3(d), the intense rate of failures occurred within the central cells (aggregation in cells 35 to 98) of Birjand WDN in 2014, which led to the increase in the kurtosis of failure rate distribution curve with a value of 58.53. The upsurge of this statistical index denoted a rise in the data distribution curve at maximum point. Meanwhile, the maximum value of failure rate in 2014 was calculated as 45.98. It must be mention that even though the maximum value of failure rate and the kurtosis of the failure rate data in 2014 have been more than its past three years, but its skewness with a value of 6.83 was more than the previous year, which caused to inclined toward the minimum values. As can be seen in Figure 7, the highest aggregation of failure rate is within a range of 0.6-1.

By observing Figure 3(e) and Table 1, a similarity between 2014 and 2015 can be concluded in terms of location and statistical distribution of failure rate. Nonetheless, it must be mentioned that even though a maximum rate of failure with a value of 61.95 took place in cell No. 46 this year, but this incident was only limited to a single cell. It is noteworthy that the length of the network in cell No. 46 is 117.6 kilometres whereas the minimum, the mean and maximum lengths of pipelines are 12, 3352, and 7912 kilometres, respectively. Therefore, the rate value was increased due to the short length of the pipeline in this cell. With a value of 2.41, the mean rate of failures in 2015 was 10.07% less than in 2014. Also as shown in Figure 8, the highest aggregation of failure rates in 2015 was calculated in a range of 0.6-1, similar to 2014.

As represented in Figure 3(f), the intensity of the rate of failures in central areas of Birjand WDN was more than its Northern and Southern areas in 2016, similar to the past five years. In terms of the failure rate, year 2016 involved a higher mean and lower skewness relative to 2014 and 2015. This observation indicates that the intensity of the rate of failures in this year became higher than the two previous years. For verification of the mentioned claim, it can be concluded that due to the results of the frequency chart for statistical data, the rate of failures in 2016 was more aggregated in a range of 1-1.4.

Kettler and Goutler (1985) reported rates of breakage for different time periods for New York, Philadelphia, St. Catharines, and Winnipeg; 0.047 (1976), 0.17 (1964-1980), 0.27 (1977-1982), and 1.10 (1980-1982) failure per kilometre per year, respectively (Kettler and Goulter, 1985). Also, according to the study conducted by Agbenowosi (2000), the rate of accidents in the United States WDN was 0.137 cases per kilometre (Agbenowosi, 2000).

According to Figure 10, the maximum standard error, standard deviation, and sample variance are respectively related to 2015 and 2014. This means that a number of cells had a highly intense rate of failures during these two years compared to the other cells within the WDN. Moreover, the statistical parameters of median, mean, and skewness of failure rate data during the examined six-year time interval (2011-2016) involved values close to each other; furthermore, the highest intensity of failure rate in terms of spatial distribution was in the central points (cells 33 to 107) within Birjand WDN.

The results also showed that during the years 2011 through 2016, the number of failures per year were 711, 933, 952, 952, 822, and 745, respectively. Therefore, the years 2013 and 2014 involved the highest number of failures, whereas 2011 had the lowest number of delinquencies.

Conclusion

The occurrence of a failure is considered as one of the main problems in the management and operation of urban WDN which can be due to a set of parameters such as hydrodynamic pressure, hydrostatic pressure, material, diameter and ages of the pipes, executive issues in connections and many more factors. Therefore, integrated management of failures is one of the major purposes of urban WDN administration. Since there are no specific patterns for assessing the failures in a WDN, senior managers require such an approach for planning and specifying an executive and economic capability in WDNs. In the present study, the data and information on the failures of Birjand WDN from 2011 until 2016 were extracted from the PM database and then classified and verified. Then, after entering the obtained data into the GIS software, they were linked to the hydraulic information of Birjand WDN in EPANET 2. In the next step, Birjand WDN was meshed in 25-hectar blocks calculating the ratio of the number of failures over the total length of pipes within each cell, the rate of failures in the cell were estimated then classified in terms of intensity. Finally, the rate of failures in different cells was analysed for each year, according to the descriptive statistical analysis technique. The obtained results showed that the central points of Birjand WDN (cells 33-107) indicated the highest rate of failures during the years 2011-2016; consequently, a special plan must be made to modify the network or manage the extent of pressure. However, while the statistical distribution of failures in various years differed from each other, they have been taken place in ranges close to one another. Consequently, through the results of the present study, an administrative point of view can be achieved in terms of the places of failures as well as the rate values in various points and different spatial distributions.

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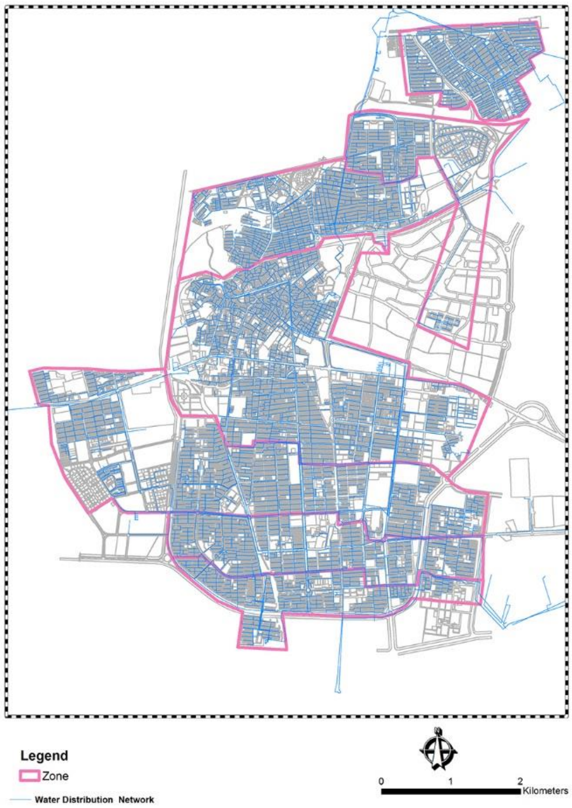
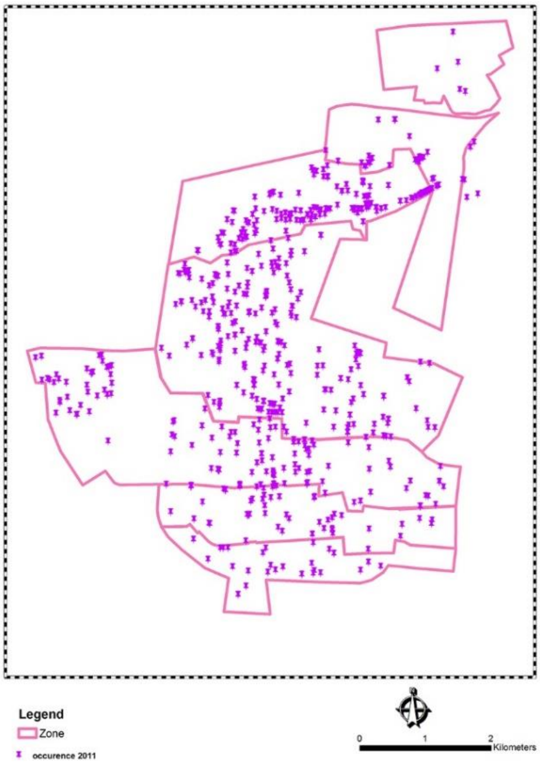
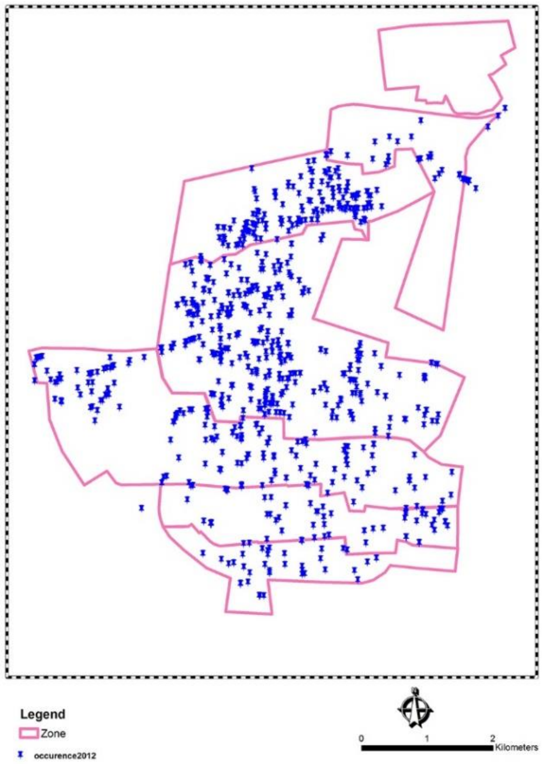
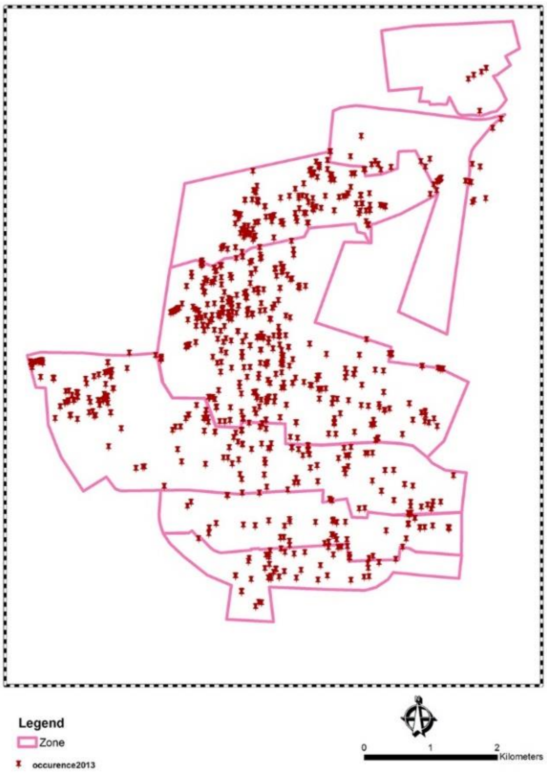


Figure 1. A view of the seven zones (pressure zones) in Birjand water distribution network.


Legend
Zone
occurence 2011
0 1 2 Kilometers


Legend
Zone
occurence2012
0 1 2 Kilometers

(a) (b)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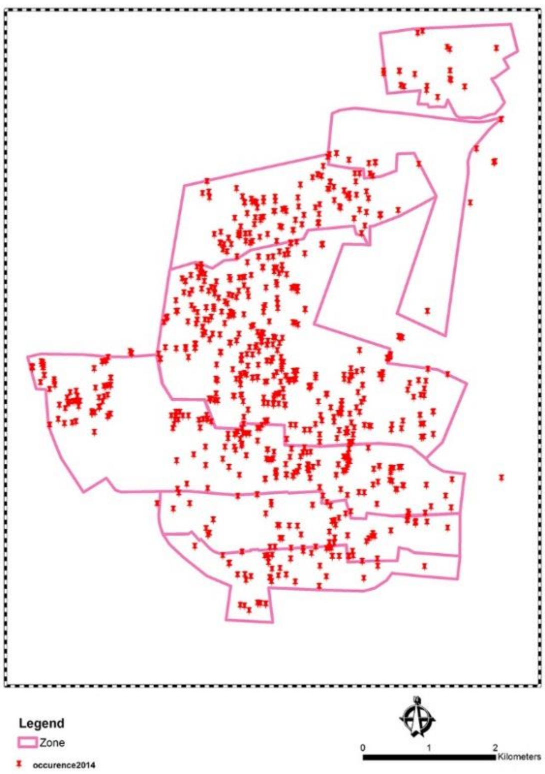
occurence2013
0 1 2 Kilometers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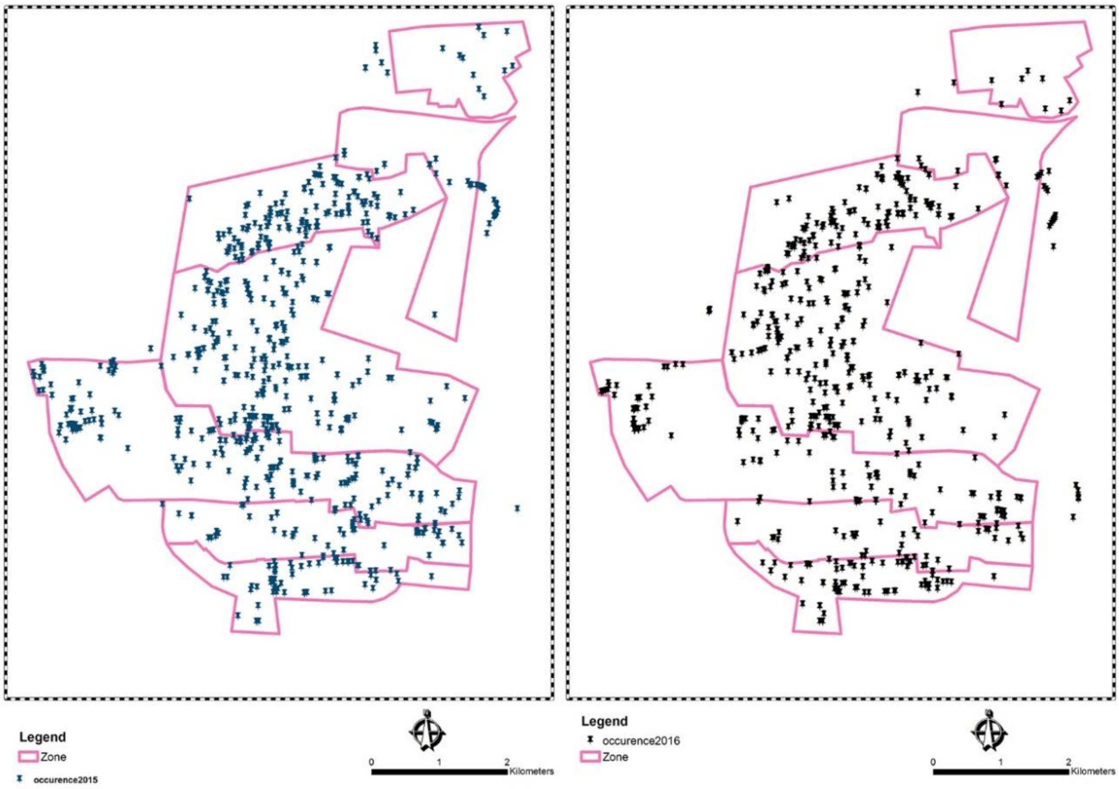
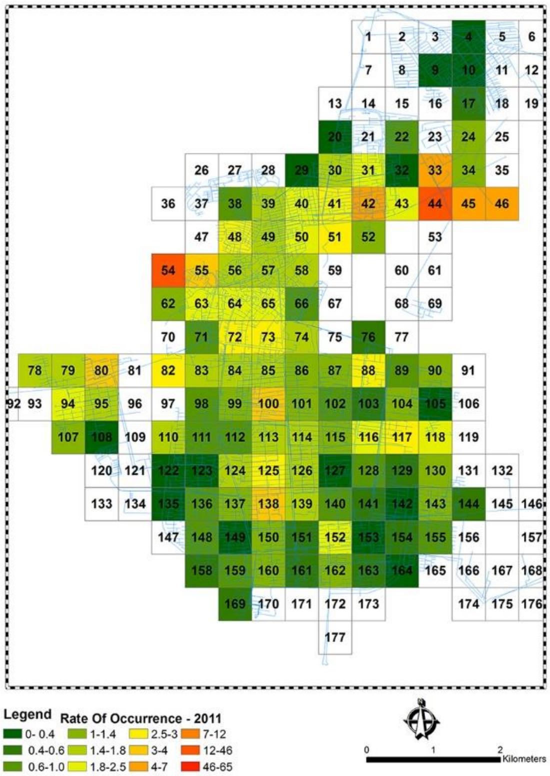
Zone
occurence2014
0 1 2 Kilometers

(c) (d)

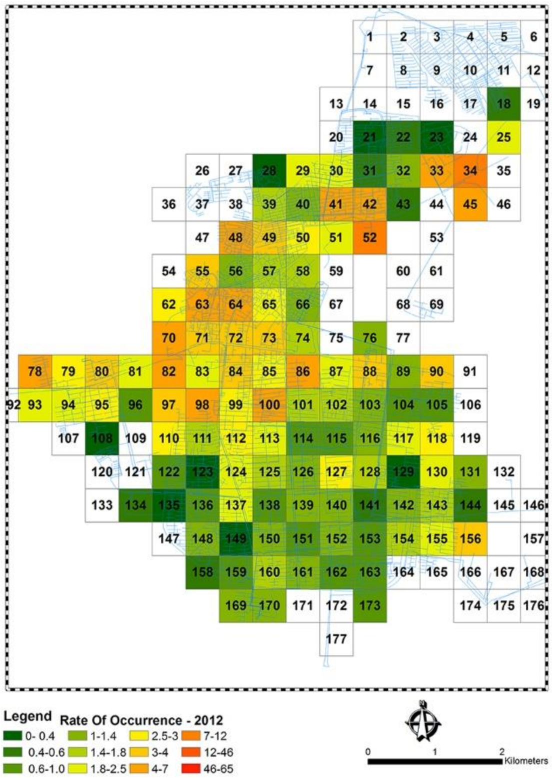


(e) (f)

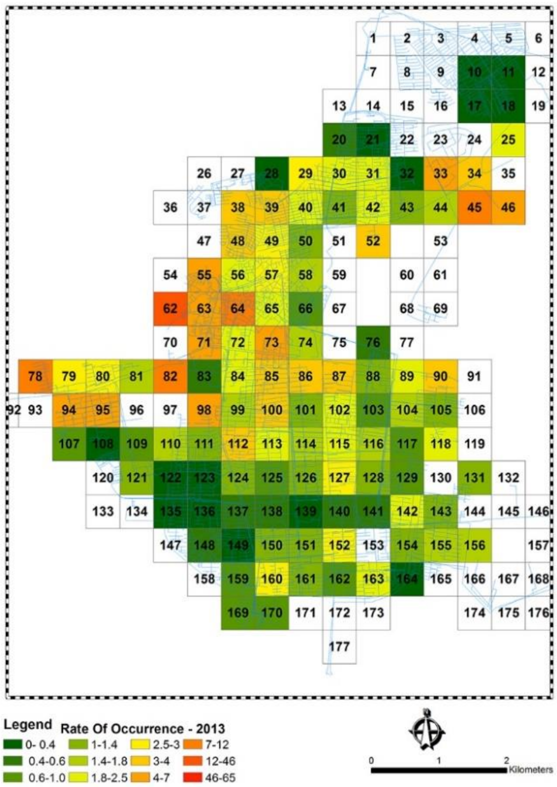
Figure 2. The failures in Birjand water distribution network during the years (a) 2011, (b) 2012, (c) 2013, (d) 2014, (e) 2015, (f) 2016.


Legend Rate Of Occurrence - 2011
0- 0.4
0.4-0.6
0.6-1.0
1-1.4
1.4-1.8
1.8-2.5
2.5-3
3-4
4-7
7-12
12-46
46-65
0 1 2 Kilometers

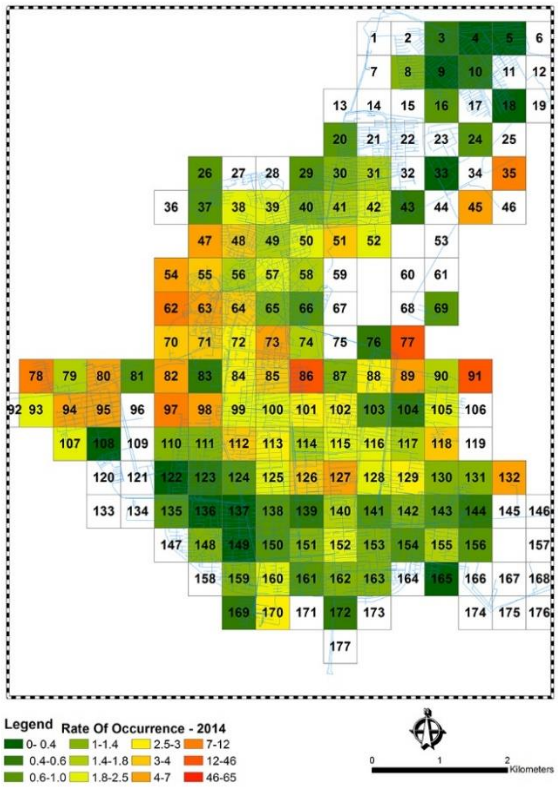
(a)


Legend Rate Of Occurrence - 2012
0- 0.4
0.4-0.6
0.6-1.0
1-1.4
1.4-1.8
1.8-2.5
2.5-3
3-4
4-7
7-12
12-46
46-65
0 1 2 Kilometers

(b)


Legend Rate Of Occurrence - 2013
0- 0.4
0.4-0.6
0.6-1.0
1-1.4
1.4-1.8
1.8-2.5
2.5-3
3-4
4-7
7-12
12-46
46-65
0 1 2 Kilometers

(c)


Legend Rate Of Occurrence - 2014
0- 0.4
0.4-0.6
0.6-1.0
1-1.4
1.4-1.8
1.8-2.5
2.5-3
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4-7
7-12
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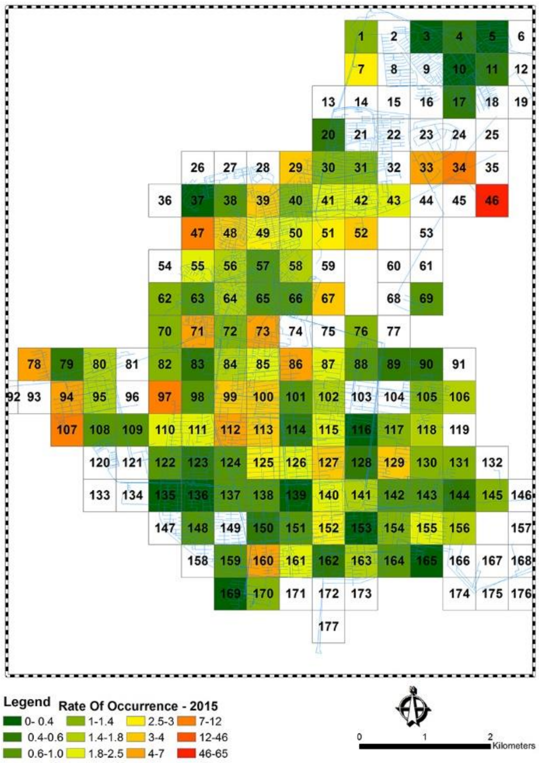
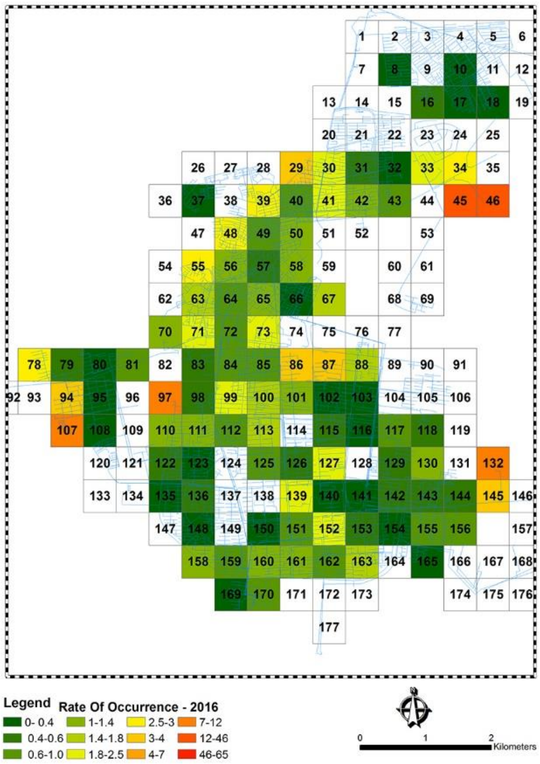
46-65
0 1 2 Kilometers

(d)



(e)



(f)

Figure 3. Meshing the rate of failures in Birjand water distribution network for the years: (a) 2011, (b) 2012, (c) 2013, (d) 2014, (e) 2015 and (f) 2016.

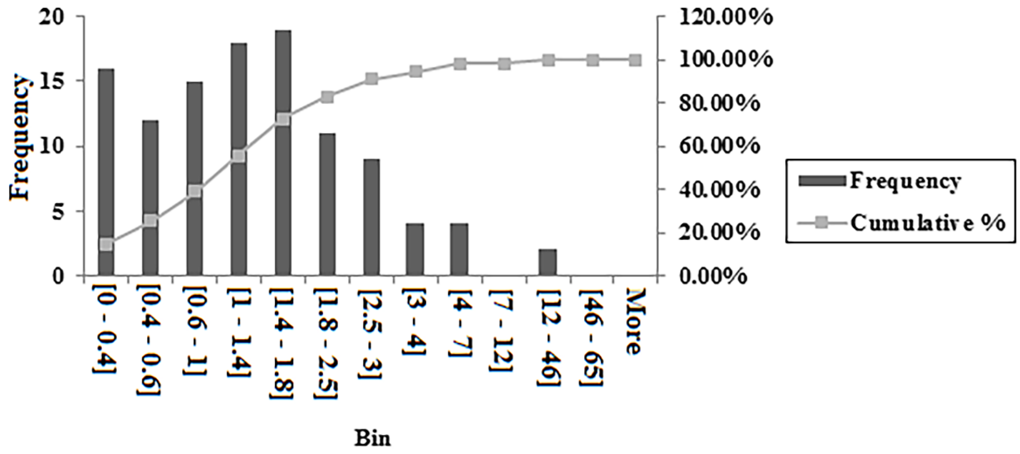


Figure 4. Histogram chart of failure rate in Birjand water distribution network in 2011.

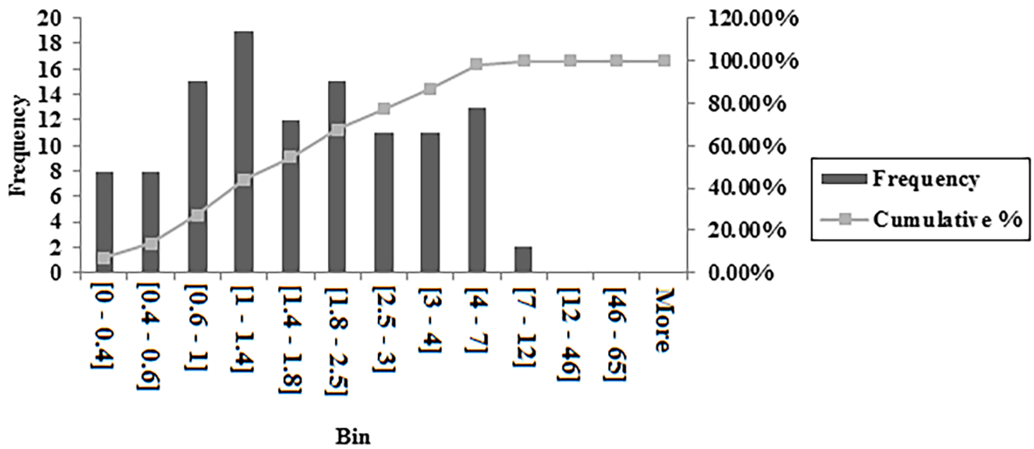


Figure 5. Histogram chart of failure rate in Birjand water distribution network in 2012.

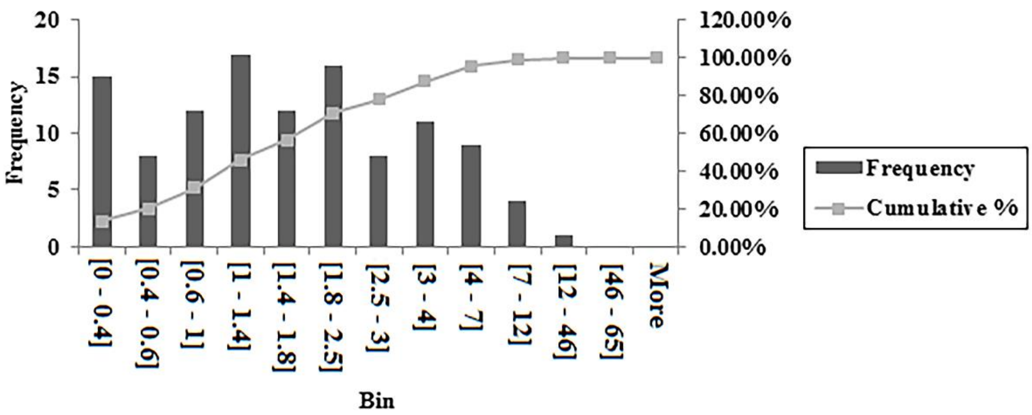


Figure 6. Histogram chart of failure rate in Birjand water distribution network in 2013.

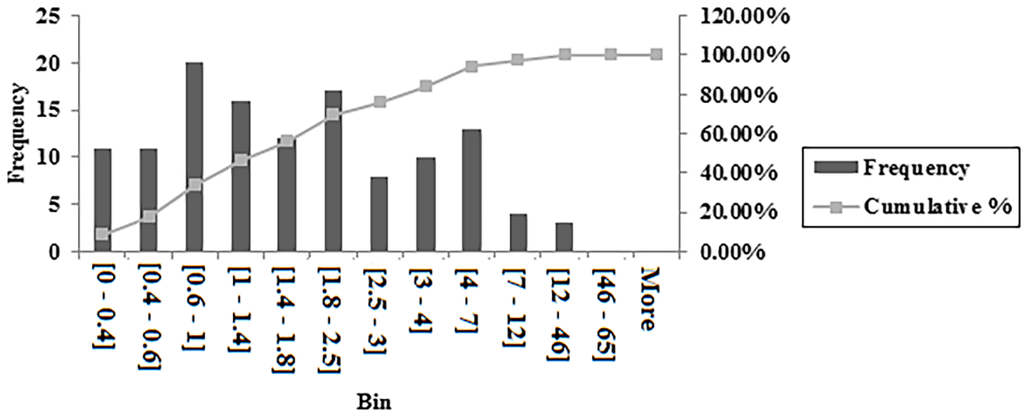


Figure 7. Histogram chart of failure rate in Birjand water distribution network in 2014.

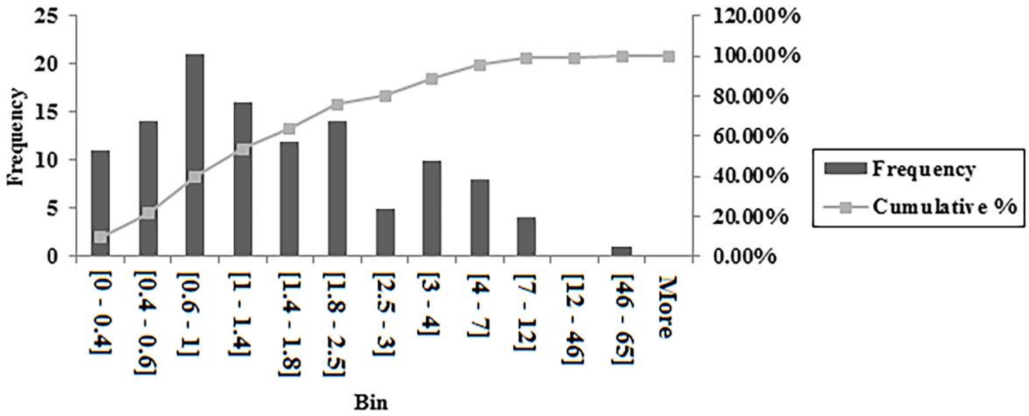


Figure 8. Histogram chart of failure rate in Birjand water distribution network in 2015.

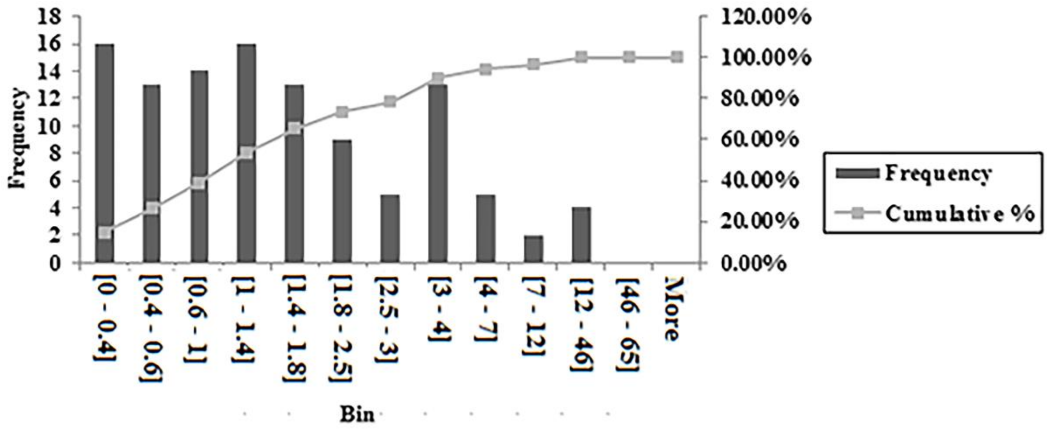


Figure 9. Histogram chart of failure rate in Birjand water distribution network in 2016.

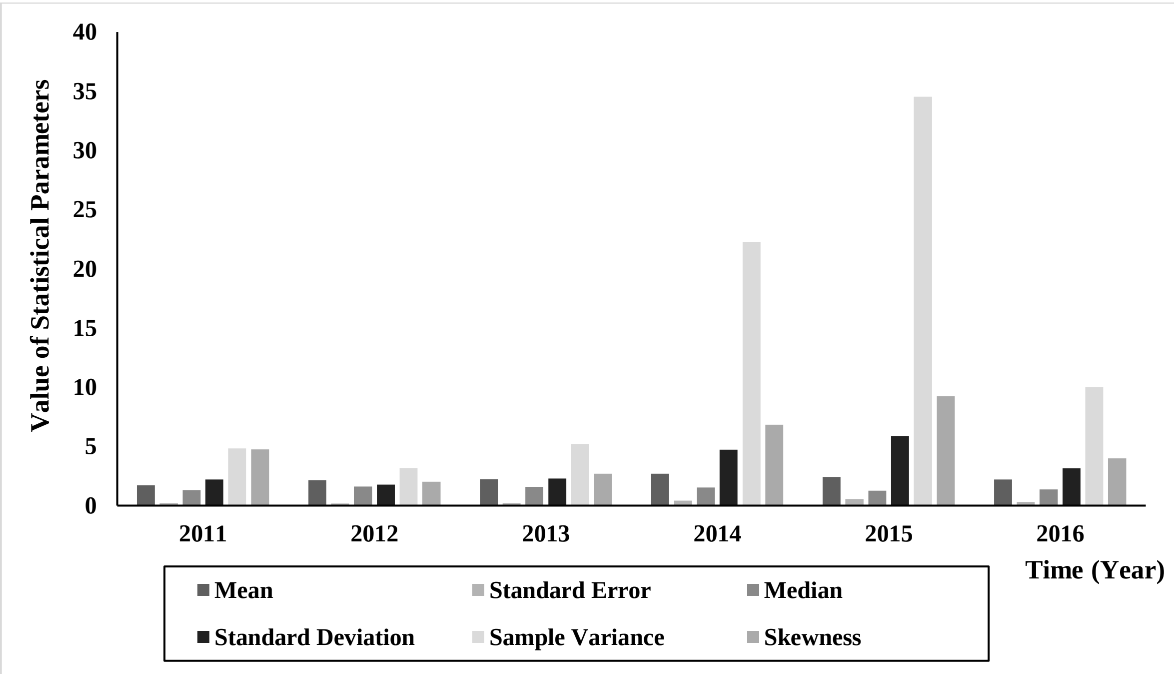


Figure 10. Comparison between descriptive statistical indices of the rate of failures in Birjand water distribution network during the years 2011-2016.

Table 1. Descriptive statistical analysis of Birjand water distribution network since 2011 to 2016.

Statistical Parameters	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Mean	1.72713129	2.158197	2.232867	2.685	2.413154	2.211495
Standard Error	0.2096567	0.167148	0.214866	0.421794	0.545675	0.30171
Median	1.318369239	1.615799	1.596153	1.533705	1.260019	1.354525
Standard Deviation	2.198898021	1.784652	2.284061	4.715803	5.877103	3.164364
Sample Variance	4.835152508	3.184982	5.216935	22.2388	34.54034	10.0132
Kurtosis	27.89179191	6.729691	9.974656	58.53554	93.45866	19.31646
Skewness	4.748655435	2.025985	2.680864	6.826405	9.243584	3.990138
Range	16.63708775	11.52575	14.79033	45.84171	61.80481	22.37478
Minimum	0.126389557	0.152582	0.167291	0.142152	0.142152	0.151387
Maximum	16.7634773	11.67833	14.95762	45.98387	61.94696	22.52617
Sum	189.9844419	246.0345	252.3139	335.625	279.9258	243.2645
Confidence Level (95.0%)	0.415532764	0.33115	0.42573	0.834849	1.080878	0.59798