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1 **Energy Metrics to Evaluate the Energy Use and Performance of Water Main Assets**

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4 **Abstract:** Managing aging infrastructure has become one of the greatest challenges for water

5 utilities, particularly when faced with selecting the most critical pipes for rehabilitation from

6 amongst the thousands of candidates. The aim of this paper is to present a set of novel yet

7 practical energy metrics that quantify energy interactions at the spatial resolution of individual

8 water mains to help utilities identify pipes for rehabilitation. The metrics are demonstrated using

9 a benchmark system and two large, complex systems. The results show that the majority of pipes

10 have a good energy performance but that an important minority of outlier pipes have a low

11 energy efficiency and high energy losses due to friction and leakage. Pumping and tank

12 operations tend to drive energy efficiency and energy losses in pipes close to water sources while

13 diurnal variation in demand drives energy performance of mains located far away from water

14 sources. The new metrics of energy lost to friction and energy lost to leakage can provide

15 information on energy performance in a pipe than is complementary to the traditional measures

16 of unit headloss and leakage flow.

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18 *Keywords:* Energy efficiency, energy metrics, friction loss, leakage loss, pipe rehabilitation,

19 water distribution systems.

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Introduction

Water distribution systems play host to a multitude of energy interactions on an hourly and daily basis. Pumps and reservoirs supply mechanical energy to the system, while water demand, pipe leaks, and frictional headloss provide output pathways for energy to leave the system, either in the form of work or heat. As water main assets in a system age and deteriorate, they become less energy efficient, with more energy leaving the system via unwanted pipe leaks and through frictional headloss (Fontana et al., 2012; Kleiner and Rajani, 2001). The challenge in managing a large, aging water distribution system is to prioritize interventions so that investment returns the largest gain in system performance (Alvisi and Franchini, 2009 and 2006, Dandy and Engelhardt, 2001).

Energy has long been used as a key concept to understand the performance of engineering systems (Pelli and Hitz 2000; Lambert et al., 1999). Energy use as a modeling concept is germane to understanding the energy performance of water main assets in distribution systems because power and energy in water distribution systems depend on pressure and flow – two quantities that are monitored continuously by water utilities (Dziedzic and Karney, 2015; AWWA, 2009; Boulos et al., 2006). While most municipalities extensively monitor their systems, few have a firm understanding of the energy efficiency of their systems. Even fewer municipalities have the capability to use pressure and flow data to understand the impact of infrastructure upgrades and operational changes on the energy efficiency of their systems (Engelhardt et al., 2000; Roshani and Filion, 2013; Hashemi et al., 2012).

To date, previous research has been focused on characterizing the system-wide energy dynamics in distribution systems. Colombo and Karney (2002) showed that diurnal demand/pressures can affect the manner in which fissures and cracks in pipes conduct leakage.

45 Results demonstrated that the more distant the leakage sources are from the water sources, the

46 higher is the energy lost from leakage and friction. While, the presence of storage was shown to

47 have a negligible effect on leakage energy, the location of the tanks did influence the leakage

48 level and pumping energy (Colombo and Karney 2005). The research underscored the important

49 role of water mains, and their proximity to pumps and tanks, on the energy balance of a system.

50   Energy metrics developed thus far have focused on the system-wide energy performance of

51 systems. Pelli and Hitz (2000) developed energy indicators to relate system-wide energy

52 efficiency to pump efficiency and reservoir location, without considering leakage impacts.

53 Cabrera et al. (2010) presented a set of metrics to characterize the system-wide energy

54 performance that includes losses to friction, leakage, and overpressure. These energy metrics

55 provide a useful set of tools to help water utility managers better understand how far their

56 systems are from an ideal energy-efficient state but fall short of being able to identify individual

57 pipes that are problematic. Building upon their earlier work, Cabrera et al. (2014b) presented

58 additional metrics to assess the energy efficiency of a pressurized system and procedures to

59 prioritize interventions on a system-wide basis. Dziedzic and Karney (2014) examined the

60 energy dynamics of groups of pipes and pumps in the Toronto distribution system. While these

61 researchers also solved the energy balance to examine the frictional losses in individual pipes of

62 the Toronto system, they did not examine the efficiency, leakage, and other energy

63 characteristics of these pipes. The current paper extends this research direction by considering

64 energy transformations that take place in the individual pipes of a distribution system.

65   The aim of this paper is to present a set of novel energy metrics that quantify energy

66 interactions in a distribution system at the spatial resolution of individual water mains. These

67 pipe-level metrics can be applied to: 1) characterize the energy performance in water mains in an

68   unimproved state to establish a benchmark prior to any rehabilitation work; 2) plan infrastructure

69   upgrades and operational changes in areas that exhibit a low energy efficiency alongside

70   information on cost, water quality, and pipe break history, and; 3) characterize the impact of

71   infrastructure upgrades and operational improvements on the energy performance of water mains

72   in a system. In this paper, the new pipe-level metrics are applied to a large *ensemble* of water

73   mains across three distribution systems to examine how system operation and system

74   improvements impinge on the spatial and temporal patterns of energy performance in drinking

75   water mains.

76   **Energy Use in a Pipe**

77   To develop a set of energy metrics, it is instructive to consider the hydraulic grade line with

78   energy inputs and outputs in a single pipe as indicated in Figure 1. Here, the pipe conveys a flow

79   Q (m^3/s) at an upstream pressure head H_s (m). The pipe delivers a pressure head H_d (m) to a

80   downstream user that imposes a demand Q_d (m^3/s) in the pipe. Users downstream of a pipe

81   impose a demand Q_d (m^3/s) that exceeds the minimum needed water use Q_{min} (m^3/s), which

82   represents the most efficient use of water by the user given best-available water technologies

83   (Vickers 2001). There are a number of reasons for this inefficient water use including household

84   leaks, inefficiencies in appliances, theft of water (AWWA 2009), water waste through inefficient

85   industrial processes (Morales et al. 2011; Friedman et al. 2011), user perception of appropriate

86   water use (Hoekstra and Chapagain 2007), and unnecessary lawn and garden watering (Askew

87   and McGuirk 2004). For the sake of generality, the pipe can have a leak that produces a leakage

88   flow rate of Q_l (m^3/s). The pipe also conveys an additional flow $Q_{ds}=Q-Q_d-Q_l$ (m^3/s) to users

89   further downstream of the pipe. The upstream pressure head H_s (m) supplied to the pipe is

90   greater than the minimum required pressure head H_{min} (m) needed to provide an acceptable

91   service to the downstream user. The difference between supplied head H_s (m) and pressure head

92   delivered H_d (m) is made up of local losses H_{local} (m) (e.g., valves, in-line turbines, blockages)

93   and the combined frictional head loss due to demand Q_d (m^3/s), leakage Q_l (m^3/s), and the

94   additional flow Q_{ds} (m^3/s) to provide water service to downstream users. The pressure head

95   delivered to downstream users H_d (m) is made up of the minimum pressure head required, H_{min}

96   (m), and surplus head, $H_{surplus}$ (m).

97   The energy components indicated in Figure 1 are defined in Table 1 and described below.

$$E_{supplied} = E_{delivered} + E_{ds} + E_{leak} + E_{friction} + E_{local} \quad \text{(Joules)} \quad\quad (1)$$

98   where $E_{supplied}$ = energy supplied to the upstream end of the pipe (Joules); $E_{delivered}$ = energy

99   delivered to the user (in Joules) to satisfy demand Q_d (m^3/s) at pressure head H_d (m); E_{ds} = energy

100   that flows out of the pipe to meet downstream user demands (Joules); E_{leak} = leak energy

101   (Joules); E_{local} = local energy losses (Joules). The term α is equal to 1.85 in the Hazen-Williams

102   friction loss model and $\alpha = 2$ in the Darcy-Weisbach model; K = pipe resistance and Δt = the

103   hydraulic time step (3,600 seconds or 1 hour) used in the 24-hour diurnal simulation.

104   **Methods**

105   *Metrics to Evaluate Energy Performance at the Pipe Level*

106   Five metrics have been developed to characterize the gross and net energy efficiencies,

107   energy needed by user, energy lost to friction, and energy lost to leakage in the pipes of a water

108   distribution network.

109   Gross and Net Efficiencies: The gross energy efficiency (*GEE*) in Equation 2 compares the

110   energy delivered to the users serviced by a pipe to the energy supplied to that pipe. The

111   theoretical maximum value for *GEE* is 100 percent, which means that all the energy supplied to

112   the pipe is delivered to its user, even though this is impossible to achieve in practice. The

113   theoretical minimum value for *GEE* is 0 percent, which means that none of the energy supplied

114   to the pipe is delivered to its users, as all the energy is lost along the pipe.

$$GEE = \left(\frac{E_{\text{delivered}}}{E_{\text{supplied}}} \right) \cdot 100\% \tag{2}$$

115   The net energy efficiency (*NEE*) in Equation 3 compares the energy delivered to users

116   serviced by a pipe to the net energy in that pipe. Here, net energy is defined as the energy

117   supplied to the pipe minus the energy supplied to users located downstream of the pipe and not

118   directly serviced by the pipe. The maximum value of *NEE* is 100 percent, where all the energy

119   supplied (exclusively to the pipe) is delivered to its users. The theoretical minimum value is 0

120   percent, where none of the energy supplied to the pipe is delivered to its users.

$$NEE = \left(\frac{E_{\text{delivered}}}{E_{\text{supplied}} - E_{\text{ds}}} \right) \cdot 100\% \tag{3}$$

121   <u>Energy Needed by User:</u> The energy needed by the users (*ENU*) at a node in Equation 4

122   compares the energy delivered to the users serviced by a pipe against the minimum energy

123   needed by those users. A value of *ENU* below 100 percent indicates that there is an insufficient

124   level of energy to meet the service expectations of the users (either in the form of flow, pressure

125   head, or both), and a value of 100 percent means that energy delivered to the users is equal to the

126   minimum energy needed to meet their service expectations. Values of *ENU* above 100 percent

127   denote a surplus energy over and above the level needed.

$$ENU = \left(\frac{E_{\text{delivered}}}{E_{\text{need}}} \right) \cdot 100\% \tag{4}$$

128   The minimum mechanical energy in the water needed to meet the minimum needs of the

129   downstream user in Equation 4 is calculated by integrating the minimum needed power by a

130   defined period of use Δt

$$E_{\text{need}} = \gamma\, Q_{\min}\, H_{\min}\, \Delta t \qquad \text{(Joules)} \qquad\qquad (5)$$

131   where γ = unit weight of water (approximately 9,810 N/m^3 at 18°C); $Q_{\min}$ = minimum water

132   use needed by users (m^3/s); $H_{\min}$ = minimum pressure head required to deliver acceptable water

133   service to users (m); Δt= time step over which minimum needed power is integrated (seconds).

134   (Note that integration can be used to calculate minimum energy needed over a continuous diurnal

135   demand period.). Determining the minimum water use ($Q_{\min}$) is difficult because minimum water

136   use varies between individual users within the same user type (Friedman et al. 2013). The

137   minimum pressure head ($H_{\min}$) required is usually determined by water utility standards but in

138   reality can vary across users depending on their subjective perception of the minimum pressure

139   required to perform their individualized water use activities (Mays 2002, City of Toronto 2009,

140   Region of Peel 2010, Denver Water 2012). In this paper, the minimum pressure of approximately

141   30 metres (m) commonly imposed by North American water utilities (City of Toronto, 2009;

142   Region of Peel, 2010; Denver Water, 2012) was used to calculate the minimum mechanical

143   energy.

144   Energy Lost to Friction: The energy lost to friction (*ELTF*) in Equation 6 compares the

145   magnitude of friction loss in the pipe (to satisfy the demand and leakage at the end of the pipe,

146   and demands downstream of the pipe) to the net energy supplied to the pipe. This indicator can

147   be used to characterize the effectiveness of pipe relining, pipe replacement, and leak repair to

148   reduce frictional losses. The metric *ELTF* can range between 0 and 100 percent, where a value of

149   0 percent means that there are no frictional energy losses in the pipe, and a value of 100 percent

150   means that all the net energy supplied to the pipe is lost to friction along the pipe.

$$ELTF = \left(\frac{E_{\text{friction}}}{E_{\text{supplied}} - E_{\text{ds}}} \right) \cdot 100\% \tag{6}$$

151   Energy Lost to Leakage: The energy lost to leakage (*ELTL*) in Equation 7 compares the

152   magnitude of energy lost to leakage relative to the net energy supplied to the pipe. The leakage

153   term in the numerator includes leak energy, E_{leak}, and the frictional energy loss along the pipe

154   required to meet the leakage flow, Q_l, at the end of the pipe $E_{\text{friction(leak)}}$ (see Table 1). The *ELTL*

155   metric can range between 0 and 100 percent, where a value of 0 percent means that there is no

156   energy loss due to leakage in the pipe and a value of 100 percent means that all the net energy

157   supplied to the pipe is lost to leakage and friction to satisfy the leak in the pipe. The *ELTL* metric

158   can be used to characterize the effectiveness of leakage repair and pressure management in

159   reducing leakage energy loss.

$$ELTL = \left(\frac{E_{\text{leak}} + E_{\text{friction(leak)}}}{E_{\text{supplied}} - E_{\text{ds}}} \right) \cdot 100\% \tag{7}$$

160   *Calculation of Energy Metrics*

161   The pipe-level energy metrics presented above are evaluated by following a number of steps.

162   First, the EPANET2 (Rossman 2000) network solver is used to calculate the hydraulic head at

163   model nodes and pipe flow in model links over a diurnal period. Because the pipe flow direction

164   may change over a day, the hydraulic head at both ends of each pipe are compared at each time

165   step and the node with the higher hydraulic head is identified as the upstream node. Further, to

166   correctly recognize to which pipes a node is an upstream node and to which pipes a node is a

167   downstream node, the mechanical energy that a pipe delivers to the users at its downstream node

168   (multiple-link node) is proportional to its flow rate and is weighted by its flow rate into its

169   corresponding downstream pipes, such that

$$\left(E_{\text{delivered}}\right)_{i,j} = \gamma \left(\frac{Q_i}{\sum_{k=1}^{m} Q_k}\right) D_j H_j \Delta t \quad \text{(joules)} \tag{8}$$

170   where $(E_{\text{delivered}})_{i,j}$ = energy delivered by pipe i to multiple-link node j (joules); D_j = demand at

171   downstream multiple-link node j located downstream of pipe i (m^3/s); H_j = hydraulic head at

172   multiple-link node j located downstream of pipe i (m); Q_i = flow in pipe i (m^3/s); m = number of

173    $k = 1, 2, 3, \ldots, m$ upstream pipes connected to the multiple-link node j. For example in Figure 2a,

174   upstream pipes P-1 and P-2 with flow rates of 1.3 litres per second (L/s) and 1.6 L/s are

175   connected to downstream node J-1 (multiple-link node) with a demand of 2.1 L/s. Pipes P-3 and

176   P-4 are located downstream of node J-1. The mechanical energy ($\gamma D H \Delta t$) delivered by Pipe 1

177   is weighted by the ratio of its flow to the total flow conveyed by the upstream pipes, or

178   1.3/(1.3+1.6).

179   Once the upstream and downstream nodes of each pipe have been determined, and the energy

180   delivered to each node resolved as described above, the hydraulic heads and pipe flows

181   simulated over the diurnal period are used to calculate the energy components in Table 1 to

182   evaluate the pipe-level metrics in Equations 2-7. An example is shown in Equation 9 where

183   hourly values of $E_{\text{delivered}}$ and E_{supplied} are aggregated together throughout the day to calculate a

184   single value of *GEE* that is representative of the entire day

$$GEE = \left[\frac{(E_{\text{delivered}})_{t=1} + (E_{\text{delivered}})_{t=2} + \ldots + (E_{\text{delivered}})_{t=24}}{(E_{\text{supplied}})_{t=1} + (E_{\text{supplied}})_{t=2} + \ldots + (E_{\text{supplied}})_{t=24}}\right] \cdot 100\% \tag{9}$$

185   *Hydraulic Proximity Indicator*

186   In the following sections of this paper, the proximity of a pipe to a water source is considered as

187   a factor that can influence the energy performance of a pipe. In anticipation of this, an indicator

188   that characterizes the hydraulic proximity of a pipe to a nearby water source is defined in

9

189   Equation 10. The hydraulic proximity indicator is based on the general observation that hydraulic

190   head or pipe flow (or both) tend to decrease as one moves away from a water source to the

191   periphery of the system where pipes generally convey smaller flow to downstream users. The

192   hydraulic proximity indicator is a function of the role of the pipe (transmission or distribution)

193   and its location relative to the water source of the system or pressure zone in which it is found. It

194   is important to note that hydraulic proximity is not an indicator of the linear distance that

195   separates a pipe from a water source, but rather an indirect indicator of the proximity of a water

196   main asset to a water source.

$$\text{Proximity Indicator} = Q \cdot H_s \ (m^4 / s) \tag{10}$$

197   in which Q is the pipe flow (m^3/s) and H_s is the hydraulic head provided at the upstream node of

198   a pipe (m) calculated with the EPANET2.0 hydraulic model. (All heads are calculated according

199   to a fixed datum of 0 m.) High values of the hydraulic proximity indicator as defined in Equation

200   10 suggest that the water main is located near a water source, whereas low values suggest that

201   the main asset is located away from a water source.

Application of Pipe-Level Metrics to Three Distribution Systems

203   The new pipe-level metrics were applied to a large *ensemble* of water mains across three

204   distribution systems to examine how system operation and system improvements impinge on the

205   spatial and temporal patterns of energy performance in drinking water mains. System #1 (Figure

206   2b) is reported in Cabrera et al. (2010) and comprises 14 pipes (40 km), an elevated tank and a

207   pumping station controlled by minimum and maximum tank levels. The system has a total daily

208   demand of 79.8 ML/day with peaks at 8 am (peaking factor of 1.3) and 4 pm (peaking factor of

209   1.3) (Figure 3). Approximately 15 percent of the total demand is lost to leakage throughout the

210   day. The leakage is assigned to the nodes using emitter coefficients in EPANET2.0 (Cabrera et

211   al., 2010). Leakage is thus a function of time and pressure. At each time step, EPANET2 is used

212   to calculate pressure head and leakage loss to evaluate the energy lost to leakage (*ELTL*).The

213   average daily pressure in System #1 is approximately 35 m.

214   System #2 (Figure 4a) is a medium-sized distribution system in the US Midwest that includes

215   1,183 pipes (166 km), 4 pumping stations and 4 elevated tanks. The water distribution system is

216   comprised of three pressure zones to overcome an elevation difference of 99.7 m to serve a

217   population of 20,000 people. The system has a total daily demand of 237.9 ML/day with an 8 am

218   morning peak (peaking factor of 1.25) and a 10 pm evening peak (peaking factor of 1.67) (Figure

219   3). The daily mean pressure is 57 m and higher than in System #1. No leakage is considered in

220   this network.

221   System #3 (Figure 4b) is a large distribution network in the US Midwest that comprises

222   27,231 pipes (5,500 km), 28 pumping stations, and 27 elevated tanks that serves approximately 1

223   million customers. This system has a total daily demand of 12,765 ML/day with an 8 am

224   morning peak (peaking factor of 1.18) and a 9 pm evening peak (peaking factor of 1.40). The

225   system has an average nodal pressure of 53 m. Leakage is modelled as a constant demand

226   assigned by area to model nodes based upon the results of a detailed leakage study conducted by

227   the water utility.

228   **Results**

229   *System #1*

230   System #1 is a simple system and thus an ideal network with which to demonstrate the new

231   pipe-level metrics by way of two management scenarios (Figure 2b). The first scenario is the

232   Baseline (B) scenario where the pipes are unimproved. The second scenario is the Leakage

233   Reduction (L) scenario where pipe leakage is reduced by 50 percent by reducing emitter

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234 coefficients in the model. In this paper, the energy metrics are dimensionless and expressed as a

235 percentage of i) energy supplied to the pipe ($E_{supplied}$), or ii) minimum energy needed at the

236 downstream node (E_{need}), or iii) the net energy in the pipe ($E_{supplied}$ - E_{ds}). For the sake of

237 consistency, numerical values of the metrics that range between 0 and 30 percent are considered

238 "low", while values that range between 30 and 70 percent are considered "moderate", and values

239 that range between 70 and 100 percent are considered "high".

240   Baseline Scenario (No Improvements): The baseline results in Table 2 indicate that the

241 presence of both frictional losses and leakage in the system produce low to moderate values of

242 *GEE* that range between 8 to 45 percent. This association is evident in the pipes closest to the

243 source and that carry higher flow rates (e.g., pipes 11, 12, 111, and 113) because these pipes

244 must convey flows destined to locations further downstream in the network. Similarly, the

245 presence of leakage in the system produces values of *NEE* that range between 29 to 76 percent.

246   The results in Table 2 indicate that pipes 22 and 113 have an *ENU* that ranges from 110 to

247 113 percent. These pipes are located between the tank (dominant source of water in this system)

248 and the highest nodal demand at junction J-22, and thus the large energy surplus reflects the

249 delivery of water to this location from the source. The pipes 31, 121, and 122 located further

250 away from the elevated tank tend to have less surplus energy, and these pipes show an energy

251 deficit and a numerical value of *ENU* that ranges between 91 to 97 percent; these pipes deliver

252 less energy to their users due to water losses between the sources and these demand locations.

253   The baseline values of *ELTF* suggest that friction losses comprise 39 to 66 percent of net

254 energy in pipes 11 and 111, both of which are in close proximity to the pumping station and

255 carry high flows. Friction comprises 1.3 to 8.0 percent of net energy in the other pipes that

256 convey smaller flows. Also, the results for leakage losses and *ELTL* suggest that pressure and not

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257   leak size (as reflected in the emitter coefficient), drives the level of leakage and results in high

258   values of *ELTL*. For example, even though pipes 113 and 123 both have a low value of emitter

259   coefficient, their proximity to the tank in a high-pressure zone causes them to have a high

260   leakage levels and high values of *ELTL* that range from 18.8 to 22.2 percent.

261   The results also show that *NEE* in Pipe 121, located far from the tank, is driven almost

262   exclusively by the demand at the downstream node of this pipe (*NEE* = 55 to 61 percent from 12

263   am to 6 am; *NEE* = 75 to 82 percent from 6 am to 6 pm), whereas the net efficiency in Pipe 11

264   near the pump is influenced by the pumping and tank operations of the system (*NEE* = 10 to 20

265   percent during pumping periods of 12 am to 3 am and 1 pm to 5 pm). This finding highlights

266   how the proximity to pumps and tanks and the role of pipes in the global hydraulic performance

267   affects the net efficiency and energy lost to friction observed in individual pipes.

268   <u>Leakage Reduction Scenario (from 15 to 8 percent of demand):</u> The results for the leakage

269   reduction scenario in Table 2 indicate that reducing leakage flow from 15 to 8 percent produces a

270   0.2 to 11.0 percent increase in the *GEE* relative to baseline because it narrows the gap between

271   energy delivered and energy supplied. This relationship is especially true for the pipes located

272   further downstream (e.g., pipes 121, 122, 123, 31 and 32). Similarly, all pipes see a 3.9 to 18.8

273   percent increase in *NEE* relative to baseline as a result of leakage reduction. A reduction in

274   leakage also increases the *ENU* (or reduces the energy deficit) by 1.7 to 10.1 percent relative to

275   baseline because energy lost to leakage is decreased in the pipes. In most pipes, a reduction in

276   leakage is tantamount to reduced pipe flow and therefore less energy lost to leakage and friction.

277   For example, a reduction in leakage produces a 0.8 to 8.0 percent decrease in *ELTF* in pipes 112,

278   113, and 121 relative to baseline. However, in smaller pipes located further downstream in the

279   system (e.g., pipes 31, 32), the friction losses tend to increase because of an increase in pipe

280   flow–a result of reduction in leakage between the water source and these pipes. Lastly, a

281   reduction in leakage causes a 47.2 to 57.3 percent decrease in *ELTL* in all pipes.

282   *System #2*

283   In System #2, the energy metrics were evaluated only for those pipes (approximately 600

284   pipes or 60 percent of the total number of pipes) that have a non-zero downstream demand.

285   Because leakage was not modelled for this system, only metrics *GEE, NEE, ENU,* and *ELTF*

286   were evaluated for the baseline scenario; the impact of interventions such as leakage reduction

287   on energy dynamics was not considered. System #2 was simulated with assumed leakage levels

288   (no leakage, 15 percent, 30 percent) and the results (not shown) suggest that the presence of

289   leakage produces a similar frequency distribution of the numerical values of the four energy

290   metrics as shown in Figures 5 and 9. The absence of leakage data for System #2 does not

291   preclude the comparison of energy dynamics in System #2 with the other two systems (Systems

292   #1 through #3).

293   The histogram results in Figure 5 show that the *GEE* follows a bimodal distribution. Here,

294   over 60 percent of the pipes have a low value of *GEE* that ranges from 0 to 10 percent while

295   approximately 14 percent of the pipes have a high value of *GEE* that ranges from 90 to 100

296   percent. It is noted that low values of *GEE* in Figure 6a do not necessarily point to a poor energy

297   performance as these pipes tend to be located near the major system components and supply a

298   large number of users downstream. Pipes with a high *GEE* tend to be located near dead-end

299   zones where most of the energy supplied to the pipe is used to satisfy demand at the downstream

300   node of the pipe. Over 90 percent of the pipes have a *NEE* that ranges from 90 to 100 percent

301   (Figure 5). Figure 6b indicates that there are trunk mains and distribution mains near pumps and

302   tanks with low to high values of net efficiency (0.1 to 80 percent).

303 The majority of pipes (almost 80 percent) exhibit a low *ELTF* between 0 and 10 percent

304 (Figure 5). However a minority of pipes (almost 15 percent) had high frictional energy losses,

305 with *ELTF* between 90 and 100 percent. These pipes are large-diameter trunk mains that carry

306 large flows with a high average unit headloss, and are located in close proximity to a pump or

307 tank. (In this paper, average unit headloss is calculated by taking the arithmetic average of unit

308 headloss in a pipe over the 24-hour diurnal period.)

309 The energy performance of two representative pipes (Pipes 463 and 926 – see Figures 4a

310 and 6) during the 24-hour diurnal period was also examined (Figure 7). Pipe 463 is a 300 mm CI

311 water main located near pumping station P1 in System #2 and conveys flows between 15-86 L/s

312 throughout the service day. Not surprisingly, the *ELTF* in Pipe 463 varies in lockstep with the

313 flow in the pipe, whereby *ELTF* varies between 0.1 to 3 percent during low-demand periods

314 and *ELTF* varies between 5 to 27 percent during high-demand periods. The net energy efficiency

315 in Pipe 463 varies widely during the 24-hour diurnal period, with values of *NEE* between 72 and

316 86 percent during high-demand periods and values between 92 to 100 percent during low-

317 demand periods. By contrast, Pipe 926 is a 150 mm CI main located near the periphery of the

318 system (Figure 4a). This pipe conveys a near-constant flow of less than 0.10 L/s. Not

319 surprisingly, *ELTF* is correspondingly low (near 0 percent throughout the whole day in Figure 7)

320 and the net energy efficiency of this pipe is at a near-constant level of 100 percent. The results

321 suggest that the energy performance (in this case efficiency and friction) of a pipe is contingent

322 on the proximity of that pipe to a pump or tank.

323 The influence of the distance between a pipe and a major component on the energy performance

324 of that pipe was examined further. This was done by plotting *ELTF* calculated with Equation 6

325 and the max/min hourly value of energy lost to friction (*ELTF*-max, *ELTF*-min, Equation 9)

326   observed over the 24-hour diurnal period against the hydraulic proximity indicator (Equation 10)

327   in Figure 8 for an *ensemble* of 684 pipes. The results suggest that *ELTF* is smaller in distribution

328   mains located further away from water sources that convey low flows and incur small losses

329   (*ELTF*-min near 0 percent). Pipes located close to water sources tend to have a value of *ELTF*-

330   max of 100 percent (this occurs during the peak demand period). Figure 8 shows a high variation

331   in *ELTF*-max in pipes located far away from water sources. This variability is likely owing to

332   differences in diameter, roughness, and service flows across the smaller water distribution mains

333   located on the periphery.

334   *System #3*

335   The energy metrics were evaluated for over 21,000 pipes, which represents approximately 77

336   percent of pipes in System #3. In general, the findings for System #3 are similar to those for

337   System #2 in that the frequency distribution of the numerical values of metrics follows a bimodal

338   shape (Figure 9). The bimodal nature of the results emphasizes the variability of energy

339   performance in complex systems when compared to a simpler system like System #1. The

340   majority of pipes exhibit a good energy performance (high net energy efficiency, small frictional

341   losses) and a minority of outlier pipes exhibit a poor energy performance (low efficiency, high

342   losses).

343   The histogram in Figure 9 indicates that approximately 80 percent of pipes have a value of

344   *GEE* that ranges between 0 and 20 percent. As noted before, low values of *GEE* do not

345   necessarily point to a poor energy performance; in these trunk pipes the majority of the energy

346   supplied to the pipe is transferred to users well downstream of the pipe and only a small fraction

347   of the energy is delivered to users at the end of the pipe. Figure 9 also indicates that 2 percent of

348   pipes have a value of *GEE* that ranges between 90 and 100 percent. In these distribution mains

349   near cul-de-sac areas, most of the energy is transferred to users directly at the end of the pipe.

350   Approximately 90 percent of pipes have a *NEE* that ranges between 9 and 100 percent (Figure 9)

351   but a minority of pipes (4 percent) have a low to moderate net energy efficiency that ranges

352   between 10 and 50 percent. A detailed analysis showed that no single factor accounted for the

353   low values of net energy efficiency in these pipes.

354   More than 95 percent of pipes have an *ENU* that ranges between 100 and 120 percent (Figure

355   9) and over 90 percent of pipes have a low *ELTF* that ranges between 0 and 10 percent. Leakage

356   performance for this system is good with over 95 percent of pipes having a low *ELTL* that ranges

357   between 0 and 10 percent. Despite this generally good performance, there are a small number of

358   outlier pipes (approximately 3 percent of total) with a moderate to high *ELTF* that ranges

359   between 40 and 100 percent. Many of these poorly performing pipes were found to be large-

360   diameter trunk mains that convey large flows from water sources to the rest of the system. A

361   small number of pipes (2.5 percent of total) were also found to have a moderate to high *ELTL*

362   that ranges between 40 and 100 percent, and this is a direct result of the assigned leakage values

363   from the water utility leakage study.

364   The diurnal variation of *NEE* and *ELTF* in select pipes of System #3 were examined (results

365   not shown). As before, the results suggest that proximity to a water source and magnitude of pipe

366   flow conveyed by the pipe are both factors that have a large impact on the diurnal variation of

367   net energy efficiency and energy lost to friction. Generally, pipes located far away from water

368   sources convey little flow (with small headloss) and have values of *NEE* near 100 percent and

369   *ELTF* near 0 percent throughout the day. In larger trunk mains located closer to water sources

370   with comparatively high flow rates, *NEE* and *ELTF* track closely with diurnal variations in

371   pumped flow in these pipes, as was also observed in System #2.

372   The influence of the distance between a pipe and a major component on the energy

373   performance of that pipe was examined in System #3. Figure 10 plots the *ELTL* and the max/min

374   value of energy lost to leakage (*ELTL*-max and *ELTL*-min over a 24-hour period) for each pipe

375   (y-axis) against the hydraulic proximity indicator (x-axis). The values of the energy loss metrics

376   *ELTL*, *ELTL*-max, and *ELTL*-min are moderate (30 to 60 percent) near water sources (proximity

377   ranges between 3,000 and 6,000 m^4/s) and moderate to high (30 to 100 percent) at the periphery

378   of the system (proximity ranges between 0 and 250 m^4/s). This relationship can be explained by

379   two factors: 1) the trunk water mains close to a water source have a low level of leakage while

380   the smaller distribution mains near the periphery of the system have a higher level of leakage,

381   and 2) the values of net energy supplied to the pipe ($E_{supplied} - E_{ds}$, denominator of *ELTL*) are

382   large and outweigh the energy lost due to leaks ($E_{leakage} + E_{friction(leak)}$, numerator of *ELTL*)

383   because of the low level of leakage at locations near water sources. There is also a high degree of

384   variability in the values of *ELTL* and *ELTL*-max near the periphery of the system as shown in

385   Figure 10 (proximity ranges between 0 and 250 m^4/s).

Comparison of Energy Metrics With Average Unit Headloss and Pressure Head

386

387   The usual practice is to use average unit headloss to identify pipes with high frictional line

388   losses and pressure head (or excess pressure head) to identify which pipes are delivering excess

389   mechanical energy to customers. Here, the energy lost to friction (*ELTF*) was compared to

390   average unit headloss to assess their effectiveness in identifying pipes with high frictional energy

391   losses. To do this, the five pipes with the highest values of *ELTF* and the five pipes with the

392   highest values of average unit headloss were selected from the *ensemble* of 1,183 pipes in

393   System #2 and their corresponding annual frictional energy loss was calculated. (Annual

394   frictional energy loss was calculated by multiplying the frictional energy loss in a pipe over the

395   24-hour diurnal period and multiplying this daily energy use by 365 days.) This was repeated for

396   System #3 (*ensemble* of 21,156 pipes). The results in Table 3 indicate the five pipes with the

397   highest values of *ELTF* and average unit headloss sorted in descending order of annual frictional

398   energy loss. Table 3 indicates that in System #2, *ELTF* and average unit headloss identified the

399   same four pipes (69, 159, 117, 41) with the highest annual frictional energy loss, and in System

400   #3, *ELTF* and average unit headloss both identified pipe 3464 as having the highest annual

401   frictional energy loss. It it noted that average unit headloss identified four pipes with higher

402   annual frictional energy loss than the *ELTF*. A possible reason for this is that average unit

403   headloss relates more directly to annual frictional energy loss than *ELTF*.

404   In Table 4, the energy needed by user (*ENU*) and energy lost to leakage (*ELTL*) were

405   compared to pressure head to determine their effectiveness in identifying pipes that experience

406   the highest energy losses to leakage. Similar to the above, the five pipes with the highest values

407   of *ENU* and the highest values of pressure head were selected from the *ensemble* of pipes in

408   System #3 and sorted in descending order of annual energy lost to leakage. (Annual energy lost

409   to leakage was calculated by multiplying the leak energy at the downstream node of a pipe over

410   the 24-hour diurnal period and multiplying this daily energy use by 365 days.) The results in

411   Table 4 suggest that the pipes identified with *ENU* and *ELTL* had higher values of annual energy

412   lost to leakage than those identified with pressure head. The metrics of gross energy efficiency

413   (*GEE*) and net energy efficiency (*NEE*) were not compared to average unit headloss and pressure

414   head. The interested reader can find the model data and the implementation code for the new

415   energy metrics in the supplemental data files appended to this manuscript.

416

Discussion

Previous research has shown that reducing leakage flow in distribution systems produces a corresponding reduction in energy use (Colombo and Karney 2002, 2005). Cabrera et al. (2010) found that leak-free systems required less energy per cubic metre of water delivered. Not surprisingly, the observations made in System #1 of this paper corroborate these observations, whereby a 50 percent reduction in leakage flow produced a near proportional decrease in energy lost to leakage and improved gross and net efficiency and reduced energy lost to friction. Additional observations on more realistic and more complex systems are needed to verify that this near one-to-one relationship holds for most systems.

The analysis of Systems #2 and #3 showed that the statistical distribution of energy performance of the pipes in these two large systems is bimodal where the majority of pipes have a good energy performance (high efficiency, low energy losses) but that an important minority of outlier pipes also have a poor energy performance (low efficiency, high energy losses to friction and leakage). The research of Dziedzic and Karney (2014) showed an asymmetrical energy performance across the Toronto distribution system such that water mains immediately downstream of treatment works had higher energy dissipation rates than pipes located further away from treatment plants. The results of the current paper corroborate this previous finding. In all three systems examined, pipes near components tended to have low gross and net efficiencies and high energy losses due to friction and leakage, while pipes located far away from components had high gross and net efficiencies and low friction and leakage losses. Pipes near components that experienced surplus pressures generally met the minimum energy needed by the users (*ENU* > 100 percent) even if their *ELTL* was generally high. However, pipes in lower-pressure regions further away from components generally fell short of meeting the minimum

440   energy needed by the users (*ENU* < 100 percent) and showed lower energy losses to leakage.

441   The findings of this paper showed that there is also a strong diurnal variation in energy

442   inputs and outputs at the scale of the individual pipe. For all systems examined, the diurnal

443   variation of energy efficiency and energy lost to friction in pipes close to components tended to

444   be influenced heavily by pumping periods and tank-draining periods when pipe flows and losses

445   were high in these pipes. Diurnal variation of energy efficiency and energy lost to friction in

446   pipes located far away from components tended to be more influenced by diurnal variation in

447   demand. These pipes had a low efficiency and high frictional losses during high-demand periods

448   and high efficiency and low frictional losses during low-demand periods. These finding support

449   the previous research that showed wide diurnal variations in global energy efficiencies in the

450   Toronto distribution system, where low frictional losses and high efficiencies were observed in

451   the night time when demand was low (Dziedzic and Karney 2014).

452   The results of this study also showed that the new metrics of *ELTF, ENU,* and *ELTL* may be

453   complementary indicators of energy performance in a pipe to the traditional indicators of average

454   unit headloss and pressure head. The results showed that the average unit headloss was on the

455   whole more successful than the *ELTF* metric in identifying pipes with the highest annual energy

456   frictional losses. This shows that average unit headloss is still an important measure because it is

457   directly tied to the pumping costs borne by a water utility. Nevertheless, the *ELTF* metric could

458   be used to evaluate the contribution of frictional losses relative to energy lost to leakage and

459   energy lost at the point of demand in pipes selected for rehabilitation with the average unit

460   headloss variable. Arguably, this could help water utilities understand the relative importance of

461   friction in the context of other energy losses in their system.

462   The results also suggested that the *ENU* and *ELTL* metrics are more successful than pressure

463 head in identifying the pipes that have the greatest energy losses to leakage. This is because *ENU*

464 and *ELTL* account for both flow and pressure head at the point of leakage that drive the

465 mechanical energy that exits the system. These results suggest that *ENU* and *ELTL* have the

466 potential to be good indicators of energy lost to leakage in distribution systems. However, the

467 results of System #1 suggest that it is the pipes that have both high pressure and high leakage

468 flow which tend to have the highest energy loss to leakage. For this reason, the results of this

469 study suggest that pressure head or leakage flow alone are not good indicators of energy lost to

470 leakage.

471   While the location of the pipe in the system has been found to have an important influence

472 on energy use, there are likely synergistic effects between the proximity to a water source and

473 other factors such as pipe diameter, pipe flow, leakage level, unit headloss that work together to

474 determine energy performance in a pipe. This paper did not examine the underlying, combined

475 effects of these key factors on the energy performance of pipes.

476   In order for the metrics of this paper to provide an accurate picture of energy performance in

477 water mains, a calibrated network model is needed with good pipe data (e.g., wall roughness and

478 diameter) and good data on the magnitude and spatial distribution of leakage. It is noted that

479 many municipalities in Canada and the US do not have good spatially-disaggregated data on

480 leakage and pipe roughness/diameter in their typically large pressure zones. Increasingly, these

481 municipalities are quantifying leakage levels and pipe flows by metering small well-defined

482 DMA (district metering area) areas that are smaller in size than traditional pressure zones. DMA

483 sectorization and flow/leak monitoring is already well-established in European countries and

484 other parts of the world and the metrics can be applied with good accuracy in these jurisdictions.

485 **Conclusion**

486 Previous research has shown the usefulness of energy metrics to examine the global or system-

487 wide energy performance of water distribution systems (Cabrera et al. 2010; Cabrera et al.

488 2014a, 2014b; Dziedzic and Karney 2014) and the balance between inputs and outputs of energy

489 through friction and leakage losses. The current paper offered a complementary approach in the

490 form of novel metrics that resolve energy performance at the spatial scale of the individual water

491 main. The results of the paper showed that average unit headloss is on the whole more successful

492 than *ELTF* in identifying pipes with high frictional energy losses, but that the new *ENU* and

493 *ELTL* metrics are more successful than pressure head in identifying pipes that experience the

494 highest energy losses to leakage. These metrics have the potential to assist water utilities in

495 understanding the energy performance of unimproved pipes alongside cost, structural and water

496 quality concerns. While outside the scope of this paper, water utilities can potentially leverage

497 this pipe-level energy analysis to perform life-cycle costing that compares the cost of pipe

498 rehabilitation against the surplus energy cost (from leakage and frictional losses) incurred in a

499 pipe when not rehabilitated (do-nothing option) to characterize the payback period of the

500 rehabilitation intervention.

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582   Table 1. Energy inputs and outputs linked to fluid flow in a pipe.

583   Table 2. Numerical values of metrics *GEE, NEE, ENU, ELTF,* and *ELTL* for the baseline and

584   leakage reduction scenarios in System #1 (reported in Cabrera et al. (2010). *GEE:* Gross Energy

585   Efficiency; *NEE:* Net Energy Efficiency*; ENU:* Energy Needed by User; *ELTF:* Energy Lost to

586   Friction; *ELTL:* Energy Lost to Leakage.

587   Table 3. Pipes with the highest values of average unit headloss and energy lost to friction (*ELTF)*

588   in System #2 (*ensemble* of 1,183 pipes) and System #3 (*ensemble* of 21,156 pipes). (Pipes are

589   sorted by annual frictional energy loss in descending order.)

590   Table 4. Pipes with the highest values of pressure, energy needed by user (*ENU*), and energy lost

591   to leakage (*ELTL*) in System #3 (*ensemble* of 21,156 pipes). (Pipes are sorted by annual energy

592   lost to leakage in descending order.)

593

594   Table 1.

595

Energy Components	Equations
Energy supplied	$E_{\text{supplied}} = \gamma\, Q\, H_s\, \Delta t$
Energy delivered	$E_{\text{delivered}} = \gamma\, Q_d\, H_d\, \Delta t$
Minimum energy needed to meet the end-user demand in an pipe	$E_{\text{need}} = \gamma\, Q_d\, H_{\min}\, \Delta t$
Energy that flows out of pipe to meet downstream demands	$E_{\text{ds}} = \gamma\, Q_{\text{ds}}\, H_d\, \Delta t$
Leak energy	$E_{\text{leak}} = \gamma\, Q_l\, H_d\, \Delta t$
Energy lost to friction to meet demand	$E_{\text{friction(demand)}} = \gamma\,[K\,(Q_d)^{\alpha}]\; Q_d\, \Delta t$
Energy lost to friction to meet leakage	$E_{\text{friction(leak)}} = \gamma\,[K\,(Q_l)^{\alpha}]\; Q_l\, \Delta t$
Energy lost to friction (meet d/s demand)	$E_{\text{friction(ds)}} = \gamma\,[K\,(Q_{\text{ds}})^{\alpha}]\; Q_{\text{ds}}\, \Delta t,$ where $Q_{\text{ds}} = Q - Q_d - Q_l$

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607   Table 2.

Pipe	GEE (percent)		NEE (percent)		ENU (percent)		ELTF (percent)		ELTL (percent)	
	B	L	B	L	B	L	B	L	B	L
11	8	9	29	29	103	106	66	68	4	2
12	8	8	52	52	106	108	39	42	7	3
113	22	23	73	73	110	115	8	8	19	9
123	42	47	70	70	101	111	4	4	22	11
111	22	24	48	48	103	108	39	40	10	5
121	45	48	73	73	97	104	5	5	14	7
122	43	47	72	72	91	98	2	2	18	9
22	37	37	76	76	113	116	6	7	9	5
21	33	35	75	75	104	109	5	6	12	6
31	37	39	73	73	95	102	1	2	15	7
32	42	45	71	71	104	112	2	2	18	9
112	33	36	74	74	106	111	7	7	15	7

608   B = baseline scenario; L = leakage reduction scenario.

609

610   Table 3.
611

		Annual Frictional Energy			Annual Frictional Energy
Pipe ID	Average Unit Headloss (m/km)[c]	Loss (MWh)[d]	Pipe ID	*ELTF* (Percent)[e]	Loss (MWh)[d]
System #2					
69[a]	470.8	2,971.6	69[a]	99.9*[f]	2,971.5
159	277.1	963.3	159	99.9*	963.3
431	131.3	644.4	117	99.9*	178.8
117	88.9	178.8	41	99.9*	150.0
41	478.2	150.0	P-97	99.9*	59.9
System #3					
3464[b]	3.9	39,552.0	3464[b]	99.9*[f]	39,552.0
26688	2.3	28,081.6	10959	99.9*	1,313.0
9706	0.1	3,908.0	8735	99.9*	894.7
10942	0.2	1,804.4	11236	99.9*	326.0
11209	0.1	1,097.2	26528	99.9*	307.3

612

613   a. Pipes with the highest average unit headloss and energy lost to friction (*ELTF*) in the *ensemble* of 1,183
614   pipes in System #2 were sorted by annual frictional energy loss in descending order.

615   b. Pipes with the highest average unit headloss and energy lost to friction (*ELTF*) in the *ensemble* of 21,156
616   pipes in System #3 were sorted by annual frictional energy loss in descending order.

617   c. Average unit headloss was calculated by taking the arithmetic average of hourly values of unit headloss in a
618   pipe over the 24-hour diurnal period.

619   d. Annual frictional energy loss was calculated by multiplying the frictional energy loss in a pipe over the 24-
620   hour diurnal period and multiplying this daily energy use by 365 days.

621   e. Energy lost to friction (*ELTF*) was calculated by taking the arithmetic average of hourly values of *ELTF* in a
622   pipe over the 24-hour diurnal period.

623   f. Numerical values of *ELTF* were truncated to the tenth of a percent in the table.

624
625

626   Table 4.

627

Pipe ID[a]	Average Pressure Head (m)[b]	Annual Energy Lost to Leakage (MWh)[g]	Pipe ID[a]	Metric (Percent)	Annual Energy Lost to Leakage (MWh)[g]
Metric: *ENU*[c,d]					
14509	94.3	10.5	6873	123.0	17.5
14510	91.9	10.3	3443	123.4	15.8
P1379	163.1	7.3	19728	122.4	8.3
10942	92.3	6.3	19729	122.8	7.7
26572	98.8	5.3	6882	123.1	7.5
Metric: *ELTL*[e,f]					
14509	133.4	10.5	9540	99.0	52.2
14510	130.0	10.3	11538	97.4	15.5
19729	124.3	7.7	5898	97.8	15.2
10942	130.5	6.3	P423	99.5	11.1
19732	125.6	6.1	5877	100.0	10.2

628   a. Pipes with the highest average pressure head in the *ensemble* of 21,156 pipes in System #3 were sorted by
629   annual energy lost to leakage in descending order.

630   b. Average pressure head was calculated by taking the arithmetic average of hourly pressure head values in the
631   upstream and downstream nodes of a pipe over the 24-hour diurnal period.

632   c. Energy needed by user (*ENU*) was calculated by taking the arithmetic average of hourly *ENU* values in a
633   pipe over the 24-hour diurnal period.

634   d. Pipes with the highest energy needed by user (*ENU*) in the *ensemble* of 21,156 pipes in System #3 were
635   sorted by annual energy lost to leakage in descending order.

636   e. Energy lost to leakage (*ELTL*) was calculated by taking the arithmetic average of hourly *ELTL* values in a
637   pipe over the 24-hour diurnal period.

638   f. Pipes with the highest energy lost to leakage (*ELTL*) in the *ensemble* of 21,156 pipes in System #3 were
639   sorted by annual energy lost to leakage in descending order.

640   g. Annual energy lost to leakage was calculated by multiplying the leak energy (E_{leak} indicated in Table 1) at
641   the downstream node of a pipe over the 24-hour diurnal period and multiplying this daily energy use by 365
642   days.

Figure 1

Figure 1

Tank

J-10
Q: 0.0 l/s
El.: 6 m

J-11
Q: 5.0 l/s
El.: 6 m

J-12
Q: 5.0 l/s
El.: 4 m

J-13
Q: 3.0 l/s
El.: 2 m

P-1
D: 400 mm
L: 2,000 m

P-10
D: 400 mm
L: 2,000 m

P-11
D: 300 mm
L: 2,000 m

P-12
D: 350 mm
L: 2,000 m

Reservoir

Pump

P-111
D: 200 mm
L: 4,000 m

P-112
D: 250 mm
L: 4,000 m

P-113
D: 300 mm
L: 4,000 m

J-21
Q: 5.0 l/s
El.: 4 m

J-22
Q: 6.5 l/s
El.: 2 m

J-23
Q: 5.0 l/s
El.: 0 m

P-21
D: 200 mm
L: 2,000 m

P-22
D: 200 mm
L: 2,000 m

P-121
D: 200 mm
L: 4,000 m

P-122
D: 200 mm
L: 4,000 m

P-123
D: 200 mm
L: 4,000 m

J-31
Q: 3.0 l/s
El.: 4 m

J-32
Q: 3.0 l/s
El.: 5 m

J-33
Q: 3.0 l/s
El.: 0 m

P-31
D: 200 mm
L: 2,000 m

P-32
D: 200 mm
L: 2,000 m

Upstream pipes

P-1
Q: 1.3

J-1
Demand: 2.1

P-2
Q: 1.6

P-4
Q: 0.4

P-3
Q: 0.4

Downstream pipes

Q: Pipe flows (l/s)

(a)

D: Pipe diameter (mm)
L: Pipe length (m)
El: Node elevation (m)
Q: Nodal base demand (l/s)

(b)

Figure 3
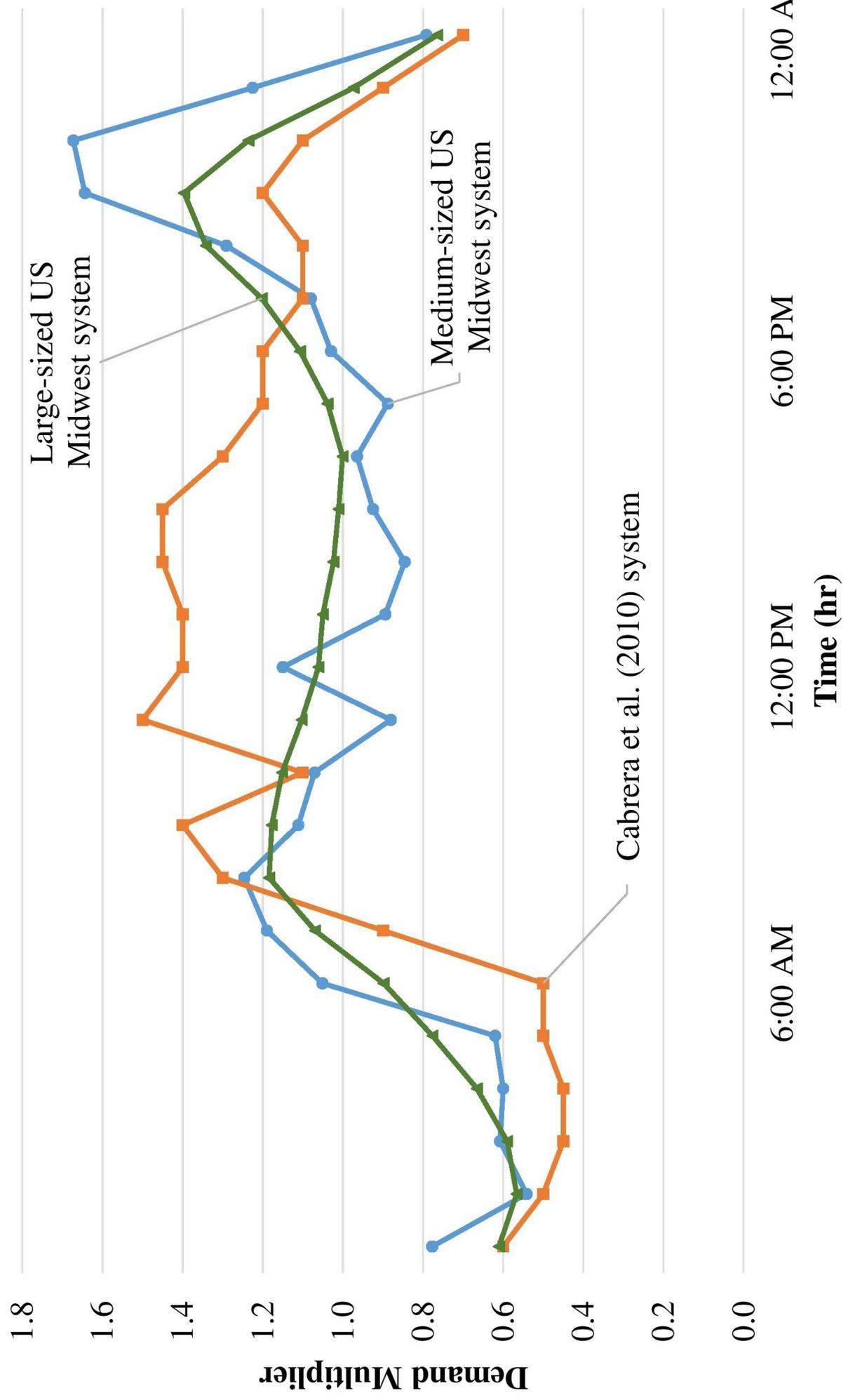
Figure 3

T2A

Pipe
P-218

P2A

Pipe 463

R, P1

Pipe 926

T1

P2

T2

P3

Pipe
P-471

Pipe
P-964

T3

T Tank

P Pump

R Reservoir

N

Legend

Pump

●

Tank

▲

Pipe

——

| 0 | 2.5 | 5 | | 10 Kilometers |

Figure 5

Figure 5

GEE (Percent)

No values
0.0-0.1
0.1-0.4
40-80
80-100

NEE (Percent)

No values
0.0-0.1
0.1-40
40-80
80-100

Figure 7
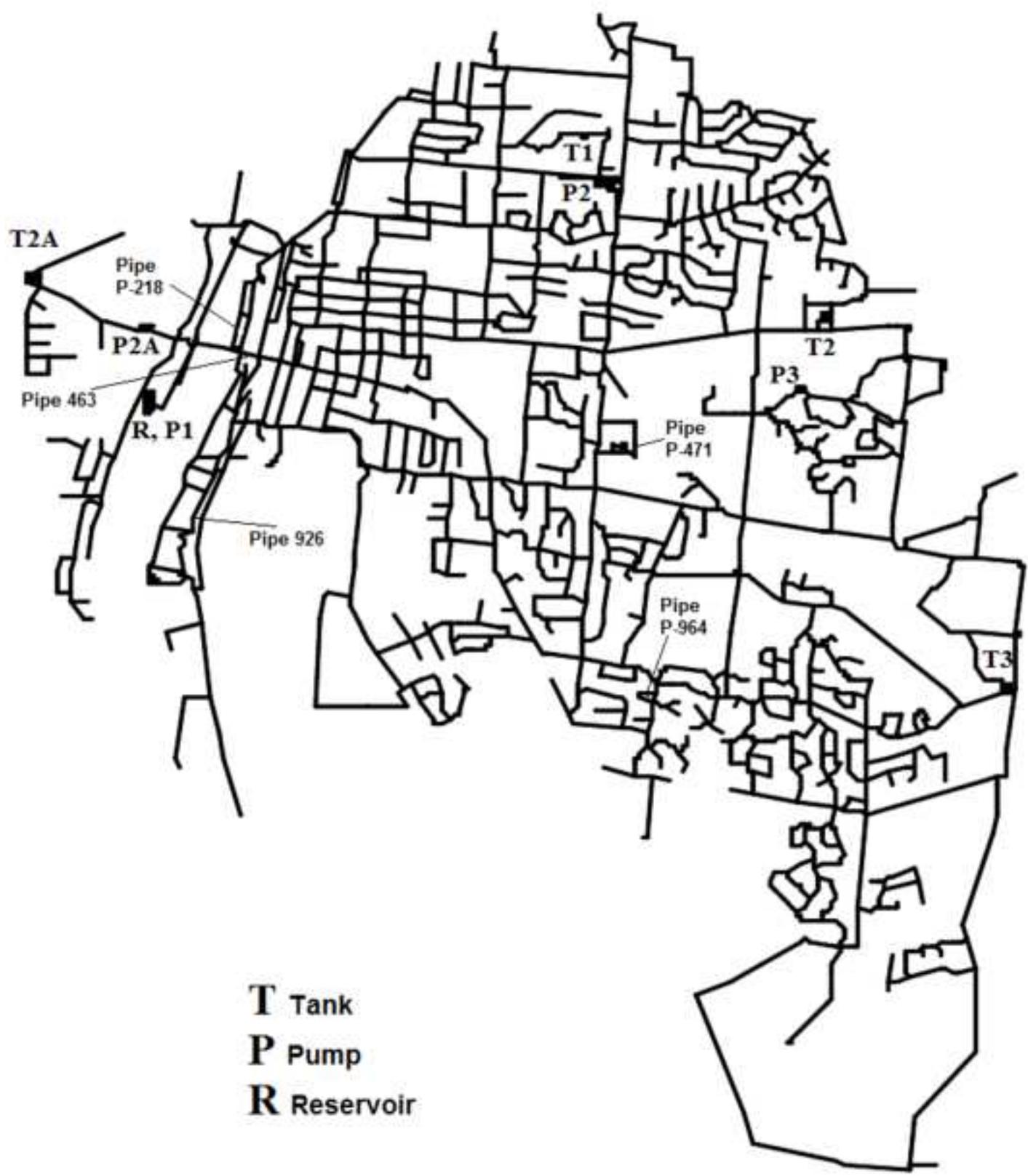
Figure 7
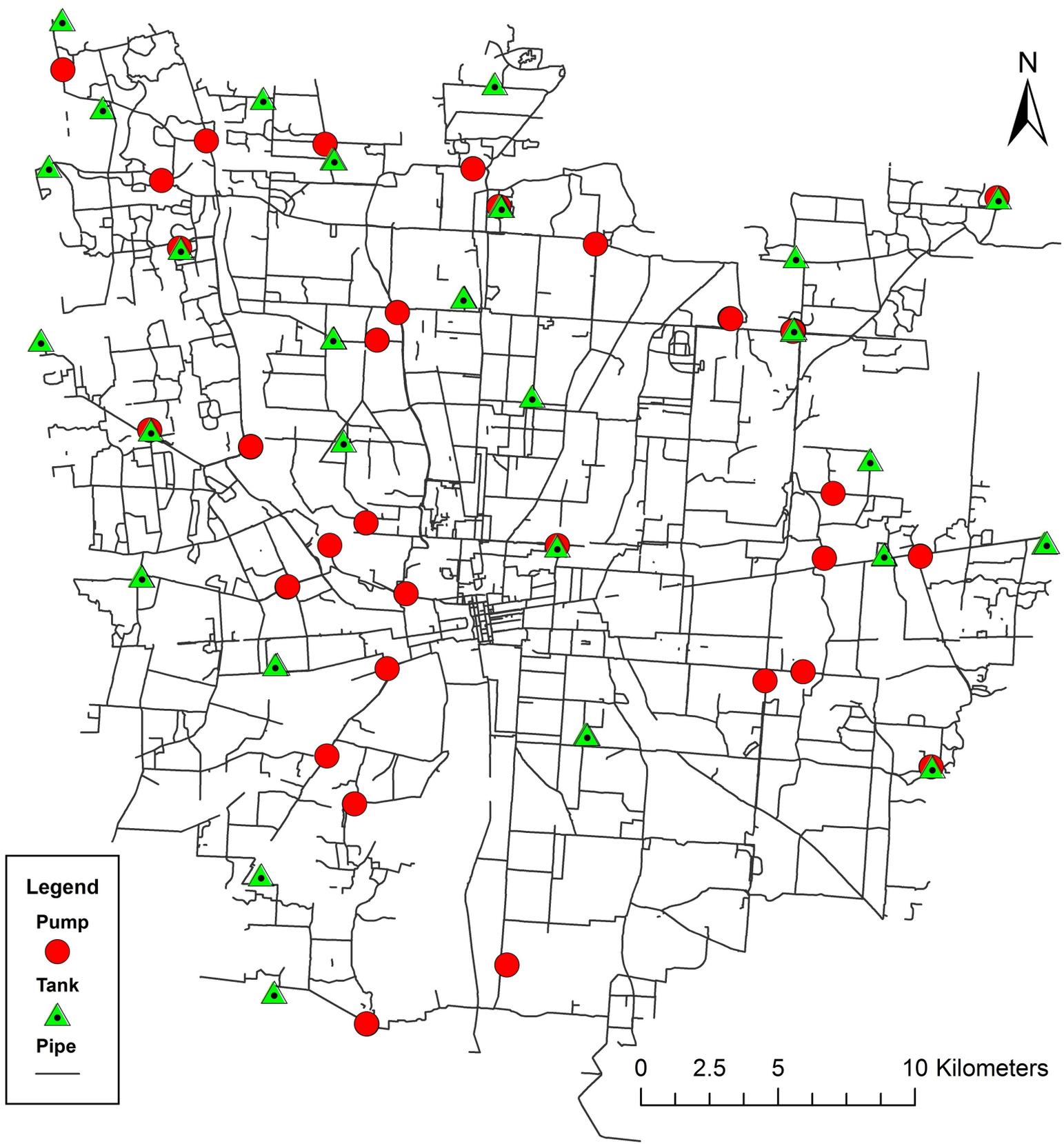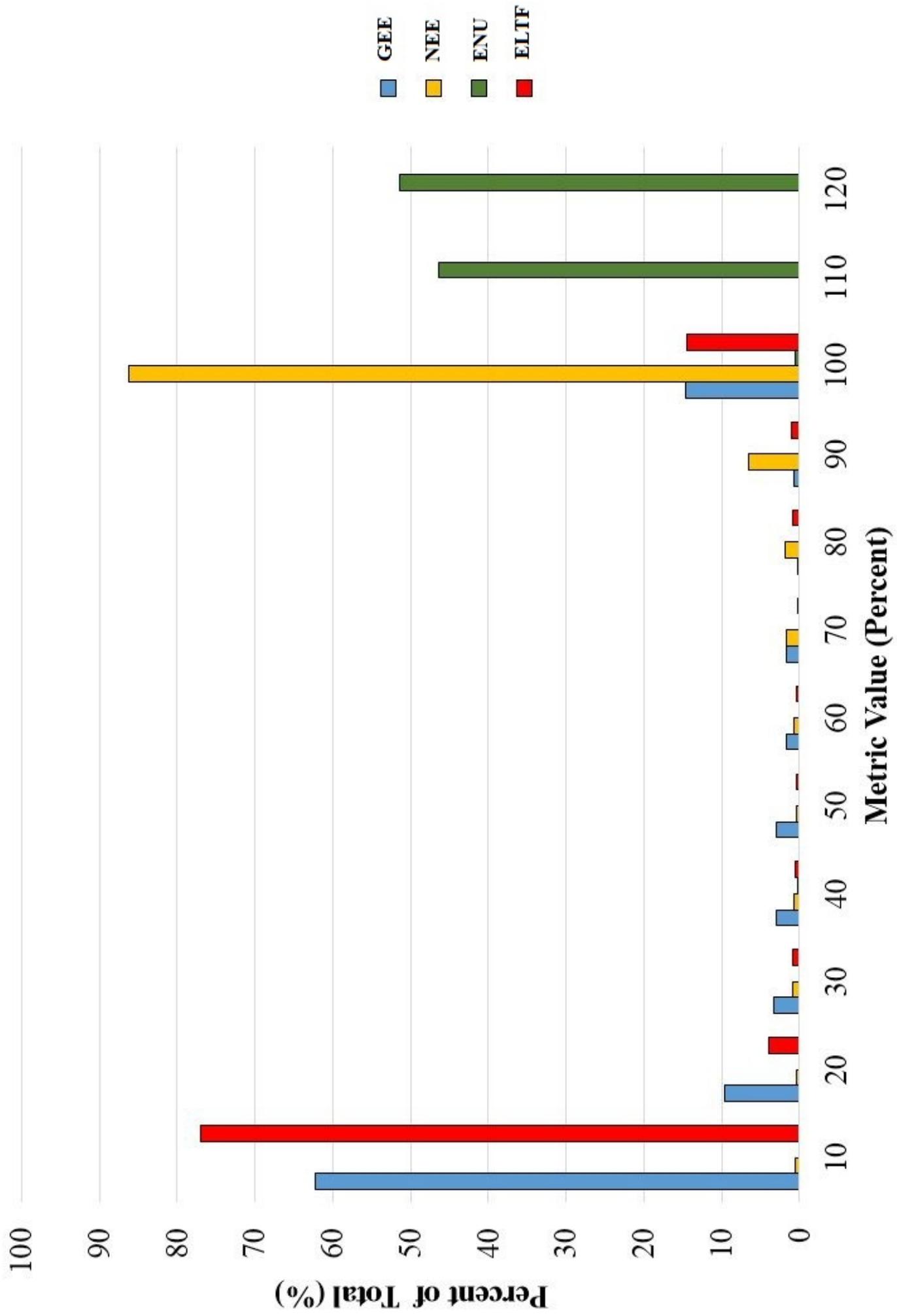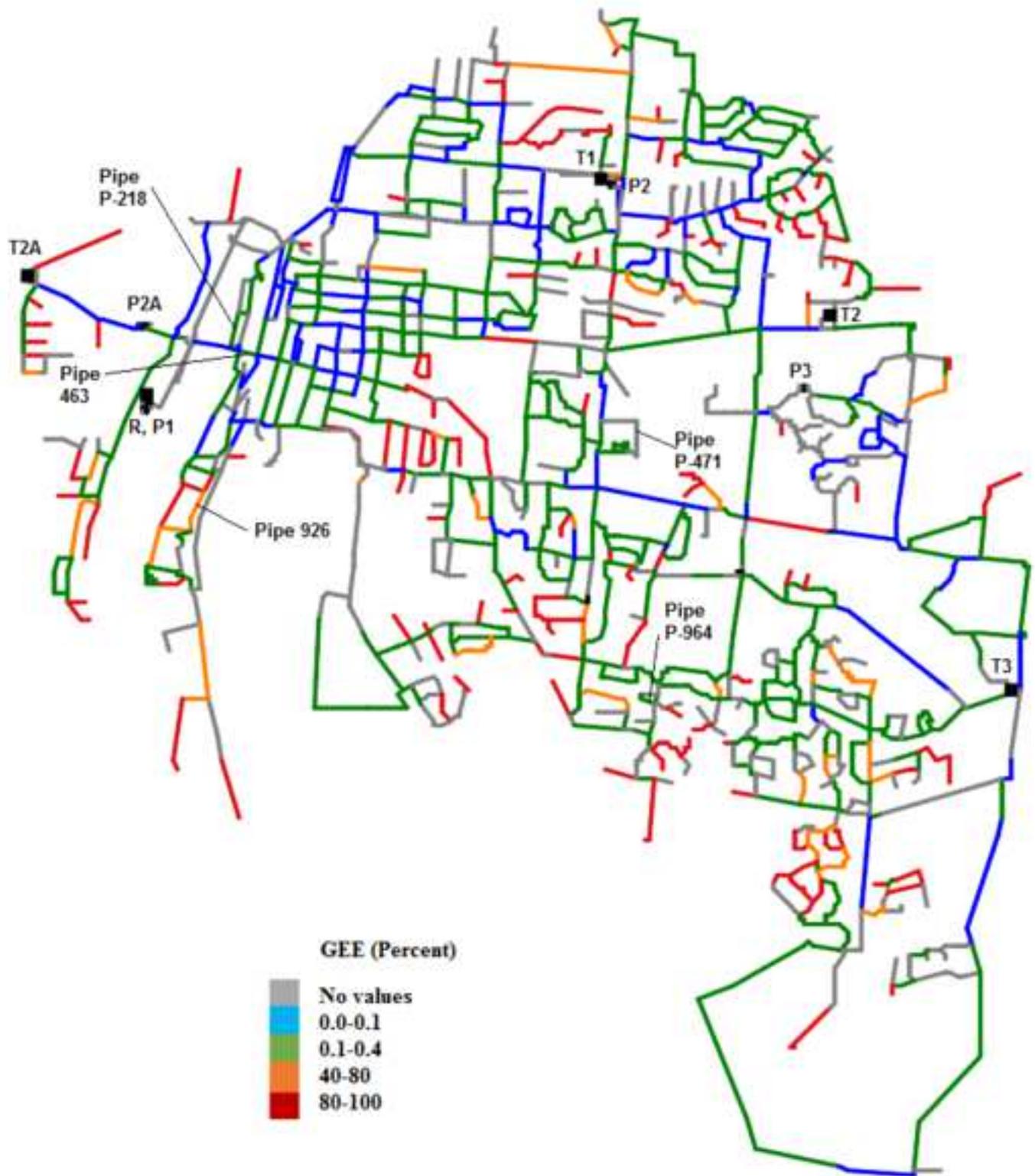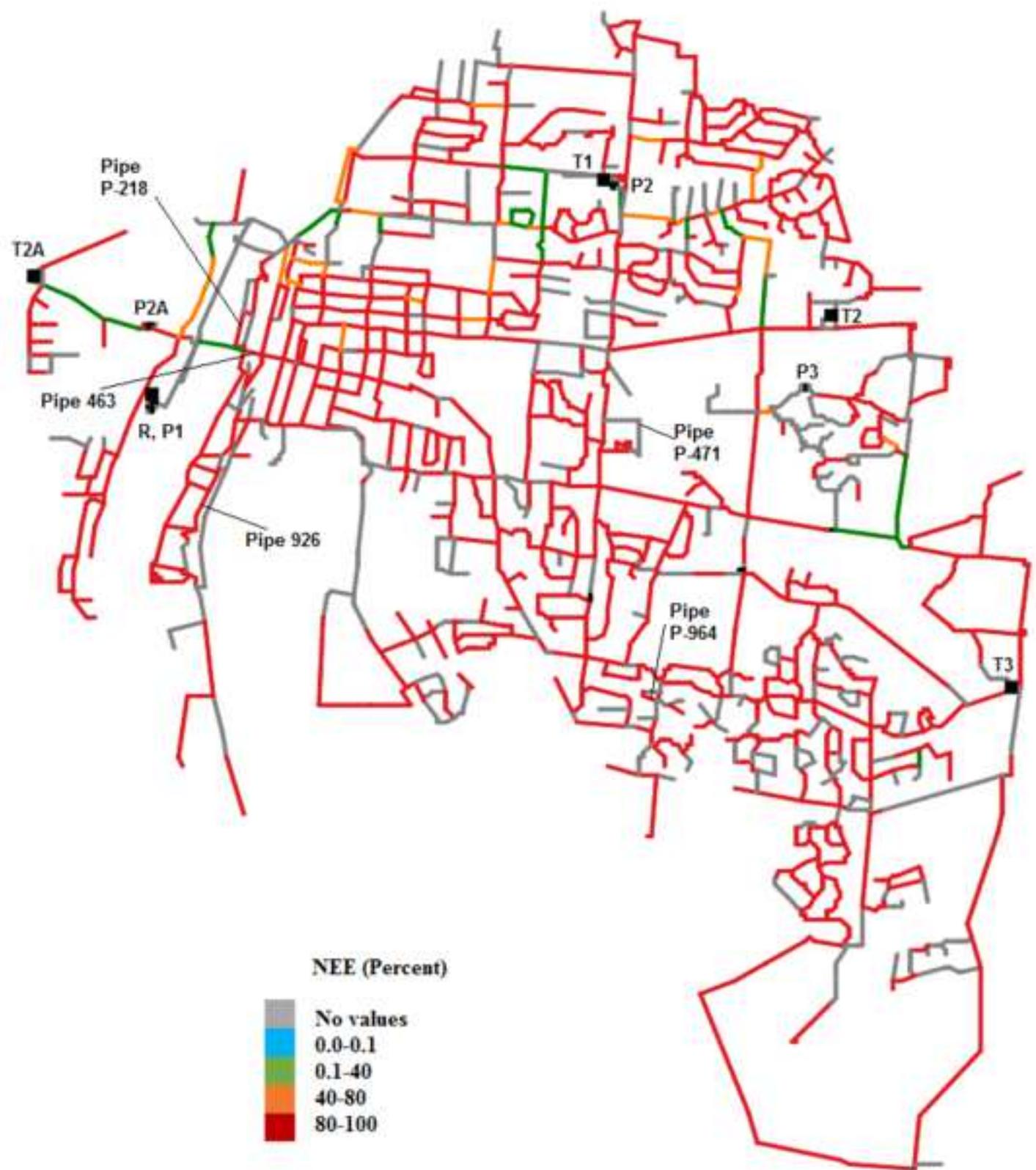
Figure 8

Figure 9

Figure 10　　　　　　　　　　　　　　　　　　Click here to download Figure Figure 10.pdf ⬇
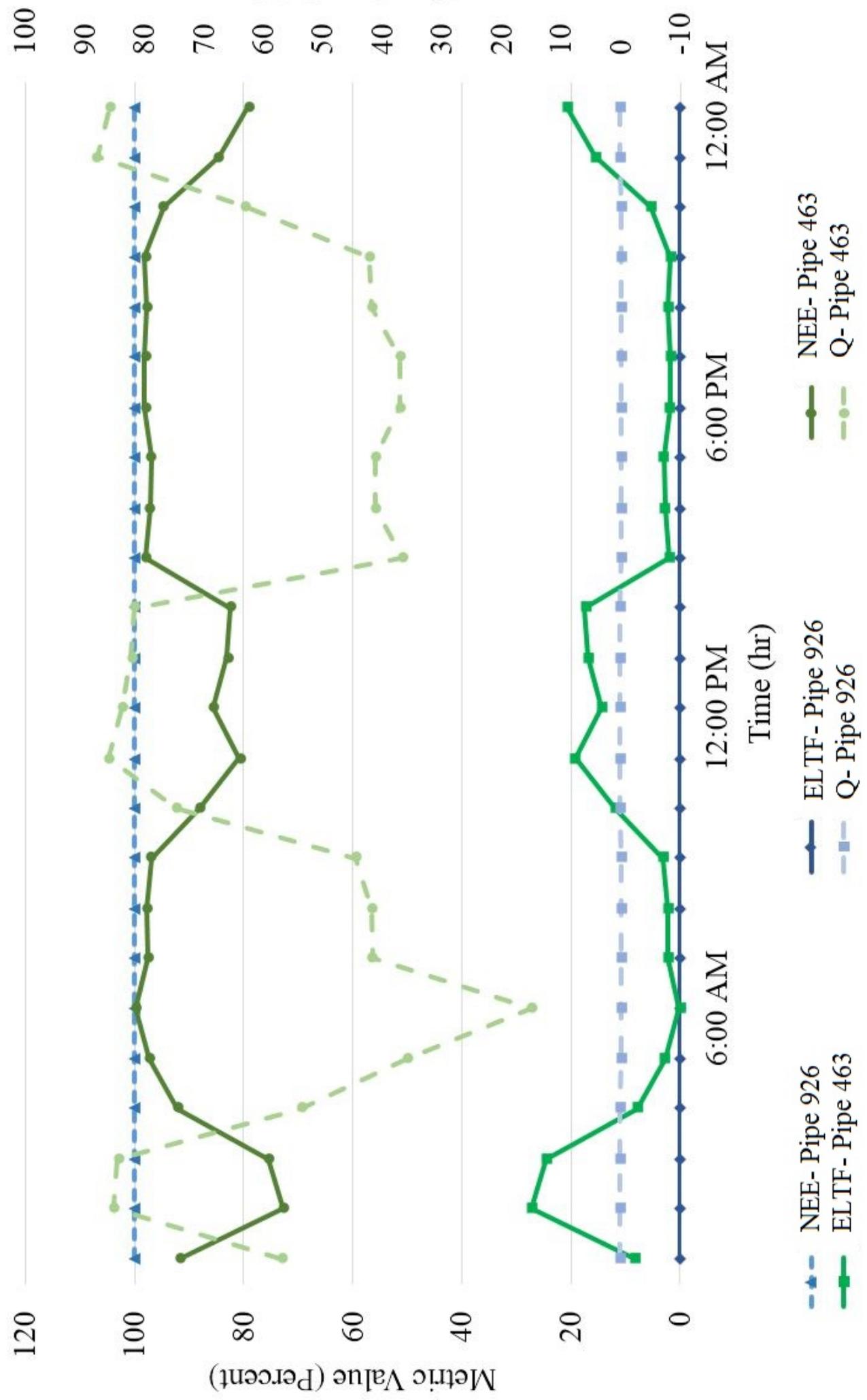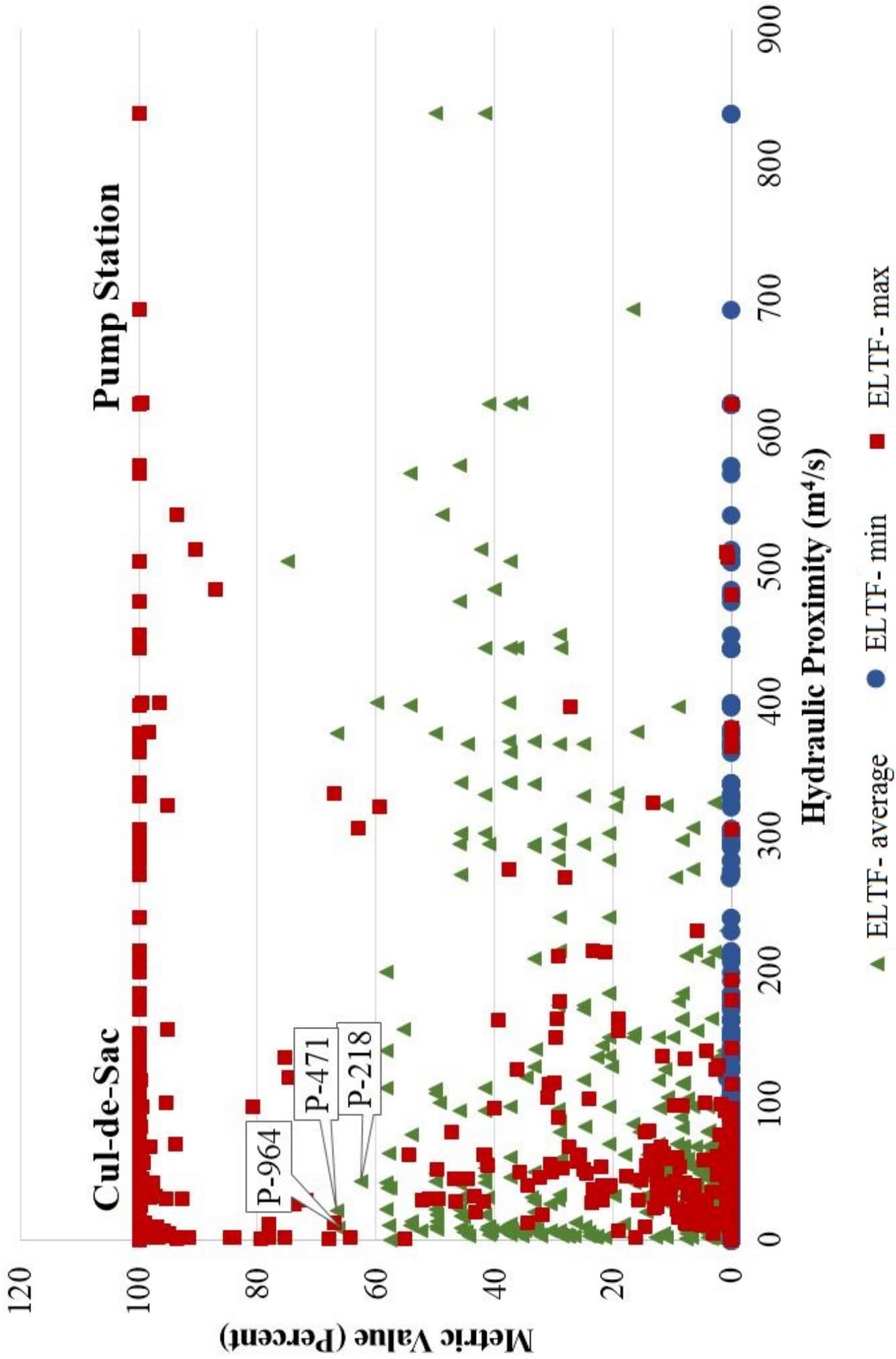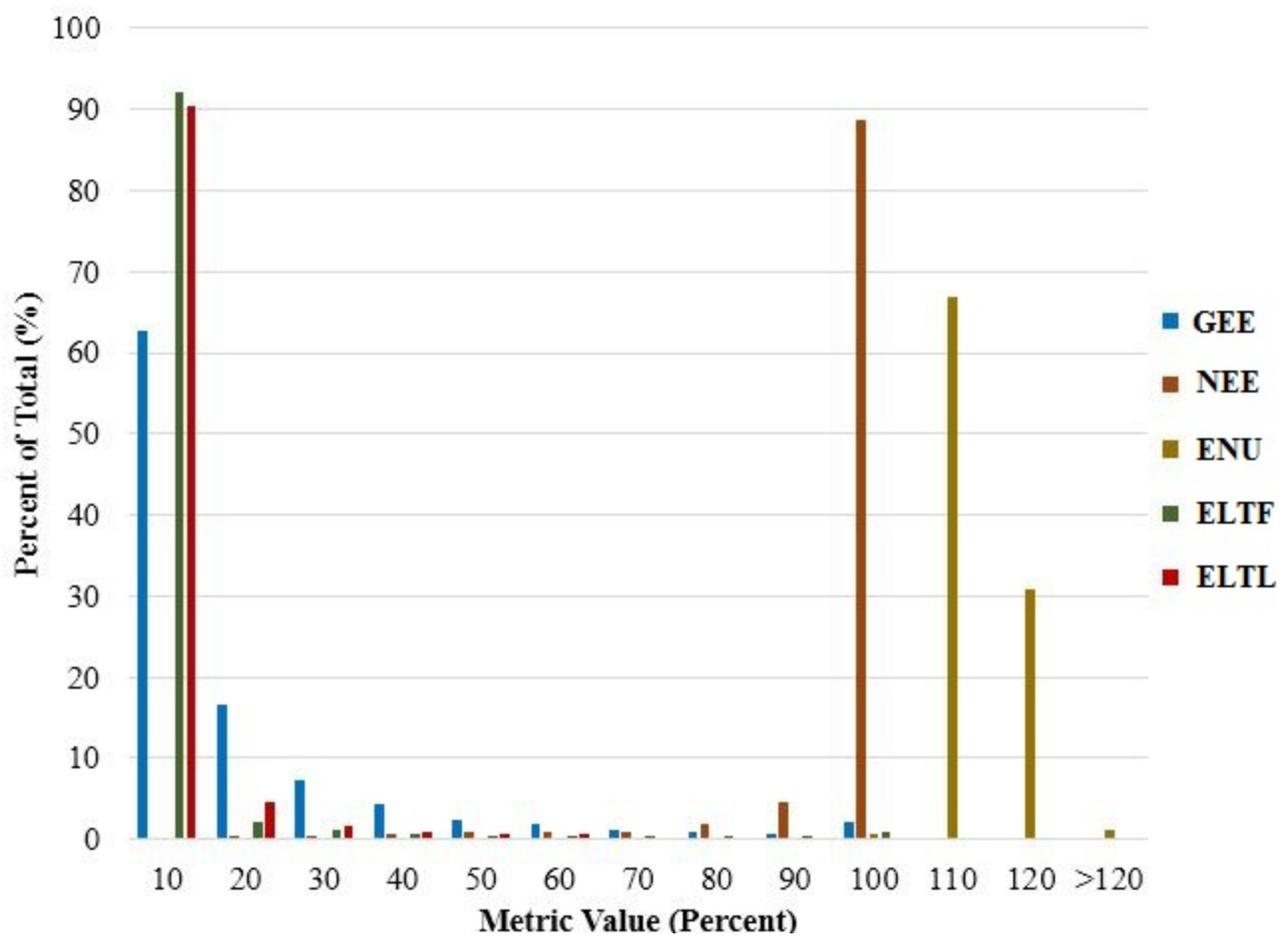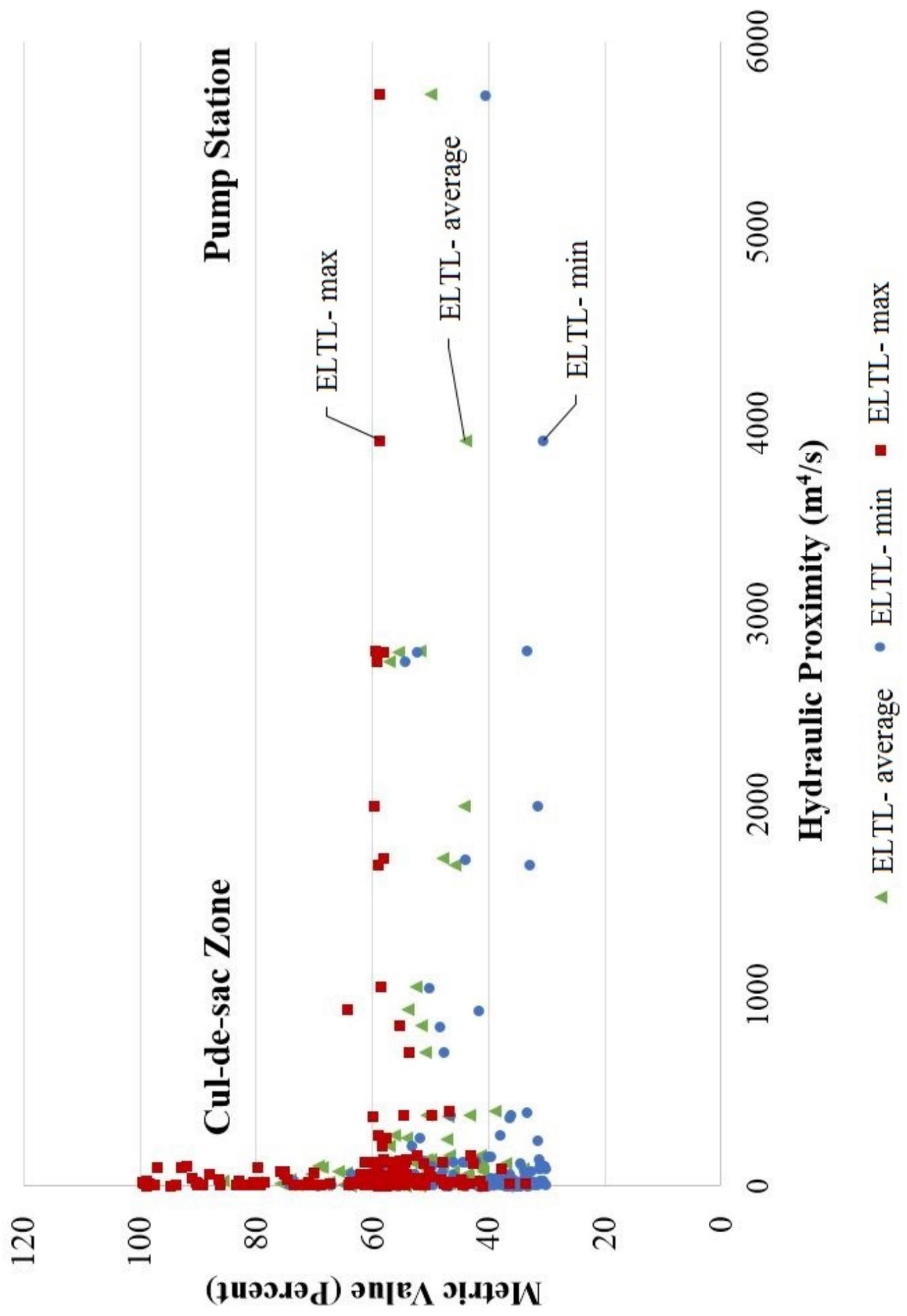
Figure 10

Figure 1. Hydraulic grade line and energy inputs and outputs in a pipe.

Figure 2. a) Example calculation of energy delivered at a model node connected to upstream and downstream pipes; b) model layout of System #1 (reported in Cabrera et al. (2010)) (L = pipe length; D = pipe diameter; P-10 = pipe ID; J-10 = node/junction ID; Q = pipe flow; $El.$ = node elevation).

Figure 3. Diurnal demand pattern for Systems #1 through #3 (24-hour period).

Figure 4. a) Model layout of System #2 (medium-sized US Midwest); b) model layout of System #3 (large-sized US Midwest).

Figure 5. Histogram that indicates the percentage of pipes with numerical values of gross energy efficiency (*GEE*), net energy efficiency (*NEE*), energy needed by the users (*ENU*) and energy lost to friction (*ELTF*) in System #2 (medium-sized US Midwest) for the baseline scenario.

Figure 6. a) Numerical values of gross energy efficiency (*GEE*) and (b) net energy efficiency (*NEE*) in pipes of System #2 (medium-sized US Midwest) for the baseline scenario.

Figure 7. Hourly values of net energy efficiency (*NEE*) and energy lost to friction (*ELTF*) in Pipe 463 (near pump station P1) and Pipe 926 (located further away from pump station P1) over the 24-hour diurnal period in System #2 for the baseline scenario. (Flow in Pipes 463 and 926 are also indicated.)

Figure 8. Energy lost to friction (*ELTF*) (as calculated in Eq. 6) and max/min values of energy lost to friction observed over the 24-hour diurnal period (*ELTF*-max, *ELTF*-min) *versus* proximity to a a pump or tank component in System #2 (medium-sized US Midwest) for the baseline scenario.

Figure 9. Histogram that indicates the percentage of pipes with numerical values of gross energy efficiency (*GEE*), net energy efficiency (*NEE*), energy needed by users (*ENU*), energy lost to friction (*ELTF*), and energy lost to leakage (*ELTL*) in System #3 (large-sized US Midwest) for the baseline scenario.

Figure 10. Energy lost to leakage (*ELTL*) (as calculated in Eq. 7) and max/min values of energy lost to leakage observed over the 24-hour diurnal period (*ELTL*-max, *ELTL*-min) *versus* proximity to a pump or tank in System #3 (large-sized US Midwest) for the baseline scenario.