ABSTRACT:

Any reliability analysis based on just deterministic values of daily average or peak demands, cannot represent the overall system reliability realistically. Using a stochastic model in this paper variations of the system and nodal reliability values are investigated through a period of time. Considering probabilistic nature of demands, this paper combines the extended period simulation of water distribution networks with the head driven simulation based reliability analysis that presents the nodal and system reliabilities more realistically than conventional demand driven simulation based analysis. A sample network with possibility of one link failure is examined and diurnal profile of reliability values due to mechanical and hydraulic failures and known probabilities of demands is presented. It is seen that considering the probabilistic nature of demands the severity of mechanical and hydraulic failures on the hydraulic performance of the system are illustrated properly and realistically, especially at the critical times or nodes, in comparison with the deterministic values.

INTRODUCTION

Reliability and damage tolerance have in recent years been firmly established as important distribution network design and operational management parameters. It is widely accepted, however, that reliability is difficult both to define and calculate in the context of water distribution systems. Although there are no universal definitions for reliability indices in water supply networks, it has been clear in recent years that in water distribution networks the reliability should be a function of the ratio of actual outflow delivered to the required demand, instead of using connectivity measures. Due to the fact that algorithms for network analysis generally treat nodal outflows as constants with pre-determined values, those algorithms are not satisfactory methods for quantifying partial water distribution system (WDS) failures. On the other hand, results from pressure dependent network analysis have shown that the consequence of insufficient pressure (i.e. insufficient outflow) tend to be localised, with conditions elsewhere often being largely unaffected (Gupta and Bhave, 1996; Tanyimboh and Tabesh, 1997). Therefore, to remove the above-mentioned shortcomings, a head driven simulation based reliability assessment method is required.

Earlier results Tabesh et al. (2002); Gupta and Bhave (1996); Cullinane et al. (1992); Fujiwara and Ganesharajah (1993) have shown that by relating the nodal outflow to the nodal pressure, the head driven simulation method (HDSM) could provide the values of actual nodal outflows and consequently, values of shortfall in water distribution networks, in a realistic manner.

Another important consideration for a more realistic evaluation of the reliability of a water supply system is to account for the variations in demand. In the literature few studies can be found in which extended period simulation has been applied for reliability purposes (e.g.
Wagner et al., 1988; Cullinane et al. 1992; Gupta and Bhave 1994; Tabesh et al. 2001). However, most of them have not focused on the variations of reliability during a time period and the extended period results have only been used to calculate the daily system reliability.

From a more realistic point of view, distribution of the average demand values through a day is not fully representative of actual variations of demand. Additionally, the daily average or peak demands vary over a long period of time and change of climate, season, day of the week. Socio-economic aspects, population, etc. also cause variations. Therefore, consideration of the probabilistic nature of demand is crucial for a realistic evaluation of the system especially when demand exceeds the design values. Exceptional demand at one or several nodes, which lead to more head loss through that part of system, is one cause of hydraulic failure. It follows, therefore, that a real reliability measure should consider a range of probable loading conditions for true assessment of the system.

Walters and Cembrowicz (1993) emphasised the probabilistic nature of demand as an important aspect of water distribution systems, alongside pipe failures, connectivity and link capacity. Also, Wagner et al. (1988) stated the usefulness of stochastic simulation methods, which can incorporate more complicated features of distribution networks and allow calculation of any desired set of reliability indices. They mentioned the inclusion of the uncertain nature of failure events and repair times. However, the stochastic nature of demand was not discussed.

More recently a stochastic simulation framework was also cast in a reliability analysis program by Gargano and Pianese (2000) and Ostfeld et al. (2002), however, the demand model of the former was complicated and needed high computational efforts and the latter was based on EPANET (a demand driven analysis model). To consider the probabilistic nature of demand, two alternative approaches may be applied. The first involves the generation of a set of random values to represent probabilistic (random) demands by a random number generation approach such as the Monte Carlo simulation method (Bao and Mays, 1990; Xu and Goulter, 1998). However, high computational requirement is one of the disadvantages of the Monte Carlo technique (Walters and Cembrowicz, 1993). Alternatively, a probability density function can be considered to account for variations of demand. This function can be made more realistic by using a set of historical field data for demands for each region (Khomsi et al., 1996).

This paper aims to present a more realistic reliability measure to evaluate water distribution networks, using the results of the head driven analysis of the hydraulics of the system. To address the effects of variable and probabilistic demands on the reliability indices, a set of extended period analyses, with both deterministic and probabilistic demands through a 24-hour day, are assessed by the proposed reliability measure.

**METHODOLOGY**

The comprehensive pressure dependent stochastic reliability analysis of water distribution systems (PDSRA) includes two major hydraulic and reliability models as follows:

**Extended Period Head Driven Simulation Model**

To perform an extended period analysis, the diurnal profile of nodal demands is needed. The required flows at each demand node are obtained by the multiplication of the daily average values with the corresponding demand factor at each time, DF(t). The demand factors themselves vary with time of day and from node to node. For design purposes hydraulic models use these factors, or a set of factors for different types of demand. It is worth noting that the resulting demand values are still deterministic for each individual time.

The hydraulic model is extended by combination of the extended period simulation
algorithm and the head driven simulation method for analysis of water distribution networks. Now having demand values at each time (hour), the nodal and system outflows and shortfalls are determined by the hydraulic model. The HDSM is established in terms of the available nodal heads and, consequently, available outflows. In this method, a nodal head-outflow relationship (herein, Wagner equation, 1988) is applied to calculate the nodal outflows.

The head-dependent outflow term can be added to the continuity equations of the system as follows, giving in general NJ equations with NJ unknowns.

\[
F_j = \sum_{i=1}^{NJ} \left( \frac{H_i - H_j}{K_j} \right)^{0.54} \text{sgn} \left( H_i - H_j \right) + Q_{j}^{\text{req}} \left( \frac{H_j - H_{j\min}}{H_{j\max} - H_{j\min}} \right)^{0.5} = 0
\]

(1)

where \(Q_{j}^{\text{req}}\) is demand at node \(j\), \(H_{j\max}\) is the desired head to satisfy the demand, \(H_j\) is the available head, \(H_{j\min}\) is the minimum head, which leads to no flow at node \(j\), and \(NJ\) is the number of nodes directly connected to node \(j\).

The second term of Eq. (1) is equal to \(Q_{j}^{\text{req}}\), if \(H_j = H_{j\max}\), is equal to zero when \(H_j = H_{j\min}\) and it is between zero and one when \(H_{j\min} \leq H_j \leq H_{j\max}\). Based on the Newton-Raphson method and choosing the nodal piezometric heads as unknown parameters, Eq. (1) is solved (Tabesh, 1998; Tabesh et al., 2002). Then using the predictor-corrector iterative procedure of Rao and Bree (1977) and Bhave (1991), the extended period analysis is performed (Tabesh et al., 2001).

**Reliability Model**

Considering the more recently and widely accepted definition for reliability as the ratio of the available flow to the required flow (demand) in conjunction with link failure probabilities, a reliability model is built as follows.

**Component Availability**

To calculate the mechanical reliability/availability the random nature of any component (pipe) failure should be accounted for by a suitable measure. Pipe availability, \(a_i\) (the probability that pipe \(i\) functions) is considered in two different ways.

i) The Cullinane et al. (1992) formulation in which the concept of the mean time to failure and duration of repair time is included, is:

\[
a_i = \frac{0.21218 D_i^{1.462131}}{(0.00074 D_i^{0.285} + 0.21218 D_i^{1.462131})} \quad \forall \ i = 1, ..., NP
\]

(2)

in which \(a_i\) is availability of link (pipe) \(i\), \(D_i\) is pipe diameter (in inches) and NP is the number of links (pipes).

ii) Having the rate of pipe breaks per km length of pipe per year, \(\mu_i\), Khomsi et al. (1996) presented the mean probability of failure of pipe \(i\) for a day (i.e. \(\mu_i L_i / 365\)) for a set of pipe diameters (Table 1). Arising from this data, the availability of pipe \(i\) is

\[
a_i = 1 - \frac{\mu_i L_i}{365}
\]

(3)

in which \(L_i\) is the pipe length (in km).
Table 1: Mean probability of pipe failures (Khomsi et al. 1996).

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean probability (km(^{-1}) day(^{-1}))</td>
<td>0.000901</td>
<td>0.000468</td>
<td>0.000192</td>
<td>0.000370</td>
<td>0.000107</td>
<td>0.000107</td>
<td>0.000071</td>
</tr>
</tbody>
</table>

**Stochastic Reliability Analysis**

According to the Khomsi et al. (1996) approach, variability of different loading conditions may be expressed by a Load Factor (LF). Using a probability density function, the probability of each load factor can be obtained. To do this, the area under the probability density function curve can be divided into several, usually equal load bands across the x-axis (such as Fig. 1). Load factor may be defined as the ratio of the required outflow to the average load for the network. Thus, load factor for any load band k, LF(k), is given by

\[
LF(k) = \frac{Q_{j}^{\text{req}}(k)}{Q_{j}^{\text{ave}}} \tag{4}
\]

in which \(Q_{j}^{\text{req}}(k)\) is the mean demand of node j in load band k. \(Q_{j}^{\text{ave}}\) is the mean demand at node j. In the absence of detailed field data for particular nodes or networks, the load factor is determined based on the data set for a particular region. The following relationship should be satisfied for the corresponding load factors and their probabilities.

\[
\sum_{k=1}^{\text{NLB}} PLF(k) = 1 \tag{5}
\]

where NLB is the total number of load bands and PLF(k) is the probability of the load factor at band k, which is computed from the normal distribution.

Considering the probabilistic nature of demand and a series of load bands under the probability distribution function, the overall system reliability (lower bound) can be written as

\[
R_{L} = p(0) \left[ \sum_{j=1}^{\text{NJ}} \sum_{l=1}^{\text{NL}} \sum_{k=1}^{\text{NLB}} r_{j}(k,t,0) \cdot PLF(k) \cdot PDF(t) + \sum_{j=1}^{\text{NJ}} \sum_{l=1}^{\text{NL}} \sum_{k=1}^{\text{NLB}} \sum_{t=0}^{\text{NT}} r_{j}(k,t,l) \cdot \frac{u_{l}}{a_{l}} \cdot PLF(k) \cdot PDF(t) \right] \tag{6}
\]

in which

\[
r_{j}(k,t,0) = \frac{Q_{j}^{\text{avl}}(k,t,0)}{Q_{j}^{\text{req}}(k,t)} , \quad r_{j}(k,t,l) = \frac{Q_{j}^{\text{avl}}(k,t,l)}{Q_{j}^{\text{req}}(k,t)} \tag{7}
\]

\(a_{l}\) and \(u_{l} (=1-a_{l})\) are the availability and unavailability of link \(l\), respectively and \(p(0)\) is the probability that all links are available.

\(PDF(t)\) is the probability of the demand factor at time \(t\), which can be obtained by a set of
historical data for any particular region, and NT is the number of time intervals. Eq. (6) represents lower bound reliability because further terms are added if more than one link failure is considered. The following relationships should be satisfied.

$$\sum_{i=1}^{NT} \text{PDF}(t) = 1$$  \hspace{1cm} (8)

$$\sum_{i=1}^{NT} \sum_{k=1}^{NLB} \text{PDF}(t) \cdot \text{PLF}(k) = 1$$  \hspace{1cm} (9)

It is worth noting that to calculate the system reliability at each individual time the summation over time and the PDF(t) factor are omitted from Eq. (6). Also, to evaluate the overall daily nodal reliability the first summation over demand nodes is omitted from Eq. (6).

Finally, besides the reliability, the proposed reliability model is capable of calculating the damage tolerance values. Damage tolerance represents the ability of the system to continue functioning even under both mechanical and hydraulic failure conditions. High values of damage tolerance represent high degree of redundancy, i.e. low vulnerability to component failure. This redundancy could be a combination of alternative supply paths to demand points, large diameter pipes with additional capacity, nearby service reservoirs with emergency storage, etc. (Tanyimboh and Templeman 1995). Lower bound damage tolerance, $T_{L}$, is calculated as follows.

$$T_{L} = \frac{R_{L} - p(0) \sum_{j=1}^{NJ} \sum_{i=1}^{NT} \sum_{k=1}^{NLB} r_{j}(k, t, 0) \cdot \text{PLF}(k) \cdot \text{PDF}(t)}{1 - p(0)}$$  \hspace{1cm} (10)

**APPLICATION**

To be able to compare the results of the various methodologies, the network of Fig. 2 taken from Khomsi et al. (1996), is chosen. The pipe and nodal data is seen in Table 2. The CHW and length of all pipes are 130 and 1000 (m), respectively. Also diameter of pipe 3-4 is 100, pipes 2-6 and 3-5 are 150, pipes 5-4 and 6-5 are 200, pipes 1-2 and 2-3 are 250 and pipe 1-6 is 300 (mm), respectively. The probabilistic distribution of demands has been obtained from a set of 14 years daily data recorded for a particular region. According to the investigations of Khomsi et al. (1996) the normal distribution was found to be the closest theoretical distribution function for this sample of data. Figure 1 shows this probability density function. As can be seen, the area under the curve of this figure is divided into five equal bands using equal divisions along the x-axis. Based on Eq. (4) the load factors and their corresponding probabilities are calculated and shown in Table 3. The diurnal profile of demand factors and their corresponding probability values at each hour, PDF(t), are presented in Table 4.

Using the proposed methodology of PDSRA, a set of analyses has been performed for this test example. To make sense of the progression of the analyses, both the extended period and steady state analyses (with the daily average values) have been performed using probabilistic demands. The results are presented and discussed next.

First, a set of probabilistic demand values has been used by an extended period reliability analysis through 24 hours. The diurnal profile of reliability and damage tolerance values with
probabilistic demands are shown in Figure 3. Table 5 shows the daily nodal and system reliabilities using probabilistic daily average demands produced by the steady state analysis. In addition, the results of Khomsi et al. (1996) are presented for comparison. It is observed that the probabilistic results are slightly lower than the deterministic ones. It can also be seen that the nodal and system reliability results of Khomsi et al. (1996) are lower than those from the PDSRA. Some explanations for differences in the two methods are presented next.

Table 2: Nodal data for the test network.

<table>
<thead>
<tr>
<th>Node</th>
<th>Daily Average Demand (m$^3$/s)</th>
<th>Minimum Head (m)</th>
<th>Required Head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.150</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>-0.020</td>
<td>158</td>
<td>178</td>
</tr>
<tr>
<td>3</td>
<td>-0.030</td>
<td>158</td>
<td>178</td>
</tr>
<tr>
<td>4</td>
<td>-0.040</td>
<td>148</td>
<td>168</td>
</tr>
<tr>
<td>5</td>
<td>-0.030</td>
<td>155</td>
<td>175</td>
</tr>
<tr>
<td>6</td>
<td>-0.030</td>
<td>174</td>
<td>194</td>
</tr>
</tbody>
</table>

Table 3: Mean load factors and their corresponding probabilities.

<table>
<thead>
<tr>
<th>Load Factor</th>
<th>Probability</th>
<th>Probability</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.56</td>
<td>0.0209</td>
<td>0.2127</td>
<td>0.4900</td>
</tr>
</tbody>
</table>

Table 4: Hourly demand factors and their corresponding probabilities (PDF).

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Demand Factor</th>
<th>PDF</th>
<th>Time (hr)</th>
<th>Demand Factor</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1.7686</td>
<td>0.07369</td>
<td>16</td>
<td>1.0978</td>
<td>0.04574</td>
</tr>
<tr>
<td>9</td>
<td>1.6170</td>
<td>0.06738</td>
<td>17</td>
<td>1.2718</td>
<td>0.05299</td>
</tr>
<tr>
<td>10</td>
<td>1.4691</td>
<td>0.06121</td>
<td>18</td>
<td>1.5983</td>
<td>0.06660</td>
</tr>
<tr>
<td>11</td>
<td>1.2607</td>
<td>0.05253</td>
<td>19</td>
<td>1.4910</td>
<td>0.06213</td>
</tr>
<tr>
<td>12</td>
<td>1.1589</td>
<td>0.04829</td>
<td>20</td>
<td>1.4484</td>
<td>0.06035</td>
</tr>
<tr>
<td>13</td>
<td>1.1220</td>
<td>0.04675</td>
<td>21</td>
<td>1.2917</td>
<td>0.05382</td>
</tr>
<tr>
<td>14</td>
<td>1.0050</td>
<td>0.04188</td>
<td>22</td>
<td>0.8642</td>
<td>0.03601</td>
</tr>
<tr>
<td>15</td>
<td>0.9528</td>
<td>0.03970</td>
<td>23</td>
<td>0.6378</td>
<td>0.02658</td>
</tr>
</tbody>
</table>

Table 5 illustrates differences between the results of the head driven simulation based analysis (PDSRA) and the demand driven simulation based analysis (Khomsi et al. 1996). Using demand driven simulation (DDSM), Khomsi et al. (1996) have shown that many nodes with load factors of 0.77 and 0.99 and all nodes with load factors of 1.21 and 1.43, face unsatisfactory heads and therefore, suffer hydraulic failure. Results of the HDSM show that the head driven analysis of the hydraulic performance of the system recognises the spatial nature of the shortfall and its results tend to be localised around critical nodes (Tabesh 1998). Generally, the resulting head loss from the HDSM is less than that from the DDSM (Tabesh et al. 2002). Therefore, by using the head driven simulation based reliability measure, fewer nodes are expected to face shortfall in heads and outflows. Thus, the head driven simulation based reliability values are seen to be higher than the results of the demand driven simulation based measures.
Table 5: System and nodal reliability and damage tolerance values considering possibility of one pipe failure (NLB=5; NT=1), using the daily average values with the snapshot analysis and Khomsi equation.

<table>
<thead>
<tr>
<th>Node</th>
<th>Deterministic Demands</th>
<th>Probabilistic Demands</th>
<th>Khomsi et al. (1996)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>T</td>
<td>R</td>
</tr>
<tr>
<td>2</td>
<td>0.999908</td>
<td>0.969975</td>
<td>0.999902</td>
</tr>
<tr>
<td>3</td>
<td>0.998824</td>
<td>0.948825</td>
<td>0.999712</td>
</tr>
<tr>
<td>4</td>
<td>0.997573</td>
<td>0.911395</td>
<td>0.990230</td>
</tr>
<tr>
<td>5</td>
<td>0.997788</td>
<td>0.915887</td>
<td>0.997319</td>
</tr>
<tr>
<td>6</td>
<td>0.998130</td>
<td>0.930690</td>
<td>0.997930</td>
</tr>
<tr>
<td>Mean</td>
<td>0.998447</td>
<td>0.935354</td>
<td>0.996919</td>
</tr>
<tr>
<td>Weighted Mean</td>
<td>0.998289</td>
<td>0.931449</td>
<td>0.996307</td>
</tr>
</tbody>
</table>
| System Reliability | 0.998282 | 0.931453 | 0.996302 | 0.922598 | 0.912600*

*a The system reliability has been calculated as weighted mean of nodal reliabilities by Khomsi et al. (1996)

Any approach which uses a 0-1 measure for reliability values such as the approach applied by Khomsi et al. (1996) is just an approximation, because it does not recognise the reduced head and partial flow modes. As the demand driven simulation cannot quantify the values of shortfall for nodal demand, they have simply used a function which takes into account the number of times at which nodal heads are insufficient. However, recognising the pressure dependency of demands, the nodal outflow varies from 100% to 0% of the demand at the node. It means that in the reduced mode from $H_j^{\text{des}}$ to $H_j^{\text{min}}$ there is still outflow, albeit less than full demand, at the node. Thus, in contrast to the PDSRA, the reliability measure of Khomsi et al. (1996) is not able to incorporate the reduced outflow and evaluates the case as a no outflow situation. Therefore, consideration of either demand driven simulation and a 0-1 reliability measure leads to lower reliability values than the head driven simulation based reliability method. This situation is illustrated especially at node 4.

Furthermore, recognising the reduced mode for partial flows and heads, the values of shortfall are quantified in terms of the required and minimum nodal heads, in the HDSM. Therefore, the higher the required nodal heads, the lower the nodal reliabilities. For instance, the reliability of node 6, which is close to the source, is lower than node 3. The cause of this is the high-required head value, i.e. 194 m, at this node, which by application of the HDSM, leads to higher shortfall and therefore, lower reliability. The Khomsi et al. (1996) method is unable to handle the above situation.

To evaluate the variations of nodal reliabilities during a day, the extended period analyses have been performed by the head driven simulation method for probabilistic demands. Figures 4 and 5 illustrate the diurnal profile for nodal reliability and damage tolerance through 24 hours, graphically. As for the system reliabilities, nodal reliability and damage tolerance values are higher at low demand times and are lower at peak demand times. For example, at 8 a.m. and 6 p.m. with the highest demands, all the system and nodal reliabilities and damage tolerances experience their lowest values. Furthermore, the severity of the failures on the performance of the system can be seen in the profile of damage tolerances at the critical times and nodes,
respectively. These show reductions from the reliability values by up to 25%.

For further investigation of the effects of probabilistic demands, a fully integrated probabilistic and extended period reliability analysis is performed to evaluate the overall daily nodal and system reliabilities. For this purpose, the full capability of Eq. 6 is used, i.e. NT=24 and NLB=5. According to this procedure the simulation's results for every node at each hour, considering the probabilistic nature of demands (using the probability density function of Fig. 1, including five different loading conditions) and the possibility of one pipe failure at each case are used as the available probabilistic nodal and system outflows. Then, using the head driven simulation based reliability measure, values of nodal and system reliability and damage tolerance are produced and presented in Table 6.

Table 6: Overall daily system and nodal reliability and damage tolerance values considering probabilistic demands and possibility of one pipe failure (NLB=5; NT=24) by the fully integrated approach.

<table>
<thead>
<tr>
<th>Node</th>
<th>Cullinane Eq.</th>
<th>Khomsi Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>T</td>
</tr>
<tr>
<td>2</td>
<td>0.999913</td>
<td>0.962019</td>
</tr>
<tr>
<td>3</td>
<td>0.983163</td>
<td>0.893505</td>
</tr>
<tr>
<td>4</td>
<td>0.904065</td>
<td>0.759852</td>
</tr>
<tr>
<td>5</td>
<td>0.938180</td>
<td>0.823463</td>
</tr>
<tr>
<td>6</td>
<td>0.941828</td>
<td>0.885970</td>
</tr>
<tr>
<td>Mean</td>
<td>0.953430</td>
<td>0.864962</td>
</tr>
<tr>
<td>Weighted Mean</td>
<td>0.947039</td>
<td>0.851484</td>
</tr>
<tr>
<td>System Reliability</td>
<td>0.947000</td>
<td>0.851490</td>
</tr>
</tbody>
</table>

Table 6 shows that the nodal reliabilities are of the same order from node 2 to node 4 (the highest and the lowest reliability). Furthermore, because of the superimposition of the probabilistic demands and extended period analysis, the effects of the probabilistic demands are clearly illustrated. In comparison with Table 5, the overall nodal reliabilities and damage tolerances from the fully integrated method (Table 6) shows lower values (by about 10% at node 4) and represent the differences of the results at each node, clearly. It is also seen that the results from the probabilistic demands are smaller than those from the deterministic demands (Table 5) by 8% for overall system reliability and damage tolerance values. While the PDSRA with steady state analysis for daily average demand produced just 1% difference with the deterministic results for the overall daily reliabilities, the values of Table 6 represent a great improvement in calculation of realistic overall nodal and system reliabilities.

SUMMARY AND CONCLUSIONS

This paper presented a step-by-step progressive stochastic reliability measure, which evaluates the hydraulic performance of water supply systems based on the head driven simulation of the network. Based on the Khomsi et al. (1996) results, it was shown that the demand driven analysis is not a suitable means to evaluate the available nodal heads and outflows and consequently, the nodal and system shortfalls in flow delivery. Therefore, it can be
concluded that any reliability measure based on results of the conventional demand driven simulation is not appropriate for water distribution networks, which face insufficient head to meet demands in any part of the system.

Also it was shown that the fully integrated extended period analysis with probabilistic demands recognised the effects of the probabilistic nature (variations) of demands over a long period (including different hourly, day of the week, seasonal effects, etc.) and could represent more realistically the overall system and nodal reliabilities and damage tolerances. However, it was unable to represent the variations of reliability for individual times of the day. To overcome this disadvantage, an overall daily reliability could be determined using equivalent values of demand-weighted mean of the hourly reliabilities resulting from the PDSRA.

REFERENCES


Figure 1: Probability density function of demand for a region in Southwest England, taken from Khomsi et al. (1996).

Figure 2: Layout of the test network, taken from Khomsi et al. (1996).
Figure 3: Diurnal profile of system reliability and damage tolerance values using the PDSRA and Cullinane equation.

Figure 4: Diurnal profile of reliability values at individual nodes.

Figure 5: Diurnal profile of damage tolerance values at individual nodes.