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RELIABILITY ANALYSIS OF POTATABLE WATER DISTRIBUTION SYSTEM

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Abstract— **The aim of this work is to investigate and analyze the mechanisms that have an effect on the reliability of potable-water distribution network in general. The general uses of the computer models have become an essential tool for the management of water distribution systems around the world. There are numerous purposes for use of a computer model to simulate the flow conditions within a system. A model can be employed to ensure the adequate quantity and quality service of the potable water resource to the community, to evaluate the planning and design alternatives, to assess the system performance and to verify a operating strategy for better management of the water infrastructure system, as well as to be able to perform vulnerability studies to assess risks that may be presented and affect the water supply. In general, a lot of studies were conducted in this field; however, the reliable network of potable water still needs to be investigated. It is the objective of this work to provide a modeler with a calibration methodology and demonstrate a software tool in which the calibration is automatically optimized. In this study, based on the described methodology, reliability analysis is performed for Bani Walid water distribution system & actual network. The results show that the hydraulic reliability of Bani Walid water distribution system is approximately 35.9%, indicating low hydraulic reliability compared to similar distribution systems. Accordingly, the study proposes several recommendations & three suggestions for actual network (case study two) to improve the hydraulic reliability of water distribution system.**

Keywords— **water distribution systems, flow simulation, water infrastructure management, risk assessment, Bani Walid water distribution system, hydraulic reliability.**

TECHNICAL TERMS:
HGL (Hydraulic Grade Line): Represents the energy level of water in a pipe system.
Hf: Losses due to friction and pipe characteristics.
Hnmax: Maximum allowable head (pressure) at a certain point.
dv/dt: Acceleration in the direction of flow.
A: Pipe cross-sectional area.

I. INTRODUCTION

Water resources are sources of water that are useful or potentially useful to humans. Uses of water include agricultural, industrial, household, recreational and environmental activities. Virtually all of these human uses require fresh water. 97.5% of water on the Earth is salt water, leaving only 2.5% as fresh water of which over two thirds is frozen in glaciers and polar ice caps. The remaining unfrozen fresh water is mainly found as groundwater, with only a small fraction present above ground or in the air. Fresh water is a renewable resource, yet the world's supply of clean, fresh water is steadily decreasing. Water demand already exceeds supply in many parts of the world, and as world population continues to rise at an unprecedented rate, many more areas are expected to experience this imbalance in the near future. As a country's economy becomes stronger, a larger percentage

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of its people tend to have access to drinking water and sanitation. Access to drinking water is measured by the number of people who have a reasonable means of getting an adequate amount of water that is safe for drinking, washing, and essential household activities. This number reflects the health of a country's people and the country's capacity to collect, clean, and distribute water to consumers. In 2000, according to the United Nations' World Health Organization (UNWHO) more than one billion people in low and middle-income countries lack access to safe water for drinking, personal hygiene and domestic use. These numbers represent more than 20 percent of the world's people at that time. Table 1.1 presents percentage of population with access to safe drinking water for 20 different countries. II. Proposed Algorithm

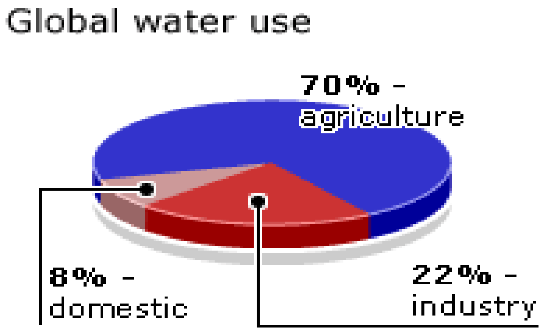

Fig. 1. Percentage usage of world water in agriculture, industry & domestic

Table.1 Percentage of population with access to safe drinking water (2000)

Country	%	Country	%
Albania	97	Algeria	89
China	75	Cuba	91
Iran	92	Iraq	85
Peru	80	Philippines	86
Syria	80	Turkey	82
Azerbaijan	78	Brazil	87
Egypt	97	India	84
Kenya	57	Mexico	88
South Africa	86	South Korea	92
Uganda	52	Venezuela	83
Chile	93	Sudan	67
Indonesia	78	Zimbabwe	83
Morocco	80		

II. METHODOLOGY OF THE PRESENT WORK

Reliability analysis of water distribution systems is carried out with focusing on hydraulic failure resulting from inability of nodal pressures to satisfy their minimum requirements.

Firstly, data relative to the selected case studies are collected. Secondly, hydraulic simulation software EPANET® is used to calculate nodal pressures for a prescribed set of generated input random variables and for random combinations of pipe closures. The selected case studies chosen in this study include existing real water supply systems in addition to hypothetical ones.

A. Water distribution systems

The early water distribution system originated during the ancient civilizations such as the Greek, Roman, Persian, Indian, and Chinese civilizations as they developed public baths. Improvement in these systems was very slow until the 19th century. Eventually the development of separate, underground water and sewage systems eliminated open sewage ditches and cesspools. Water systems of ancient times relied on gravity for the supply of water, using pipes or channels usually made of clay, lead or stone.

Present-day water supply systems is an interconnected collection of sources, pipes made of copper, brass, plastic, steel, or other nontoxic material, and hydraulic control elements (e.g., pumps, valves, regulators, and tanks) aimed at delivering water to the consumers in prescribed quantities at desired pressures.

Under economic and other constraints which exist at any specific time, the most important consideration in the planning and operation of water distribution systems is to satisfy consumer demands. The behavior of a water distribution system is governed by:

1. Physical laws that describe the flow relationships in the pipes and hydraulic control elements.
2. Consumer demand. System layout

III. OBJECTIVES OF THE STUDY

Reliability analysis of water distribution systems is useful in identifying the critical locations of junctions in a network where pressure heads are not enough to fulfill the minimum requirements to satisfy consumer demand. It helps in improving the reliability level by providing some pragmatic solution of the problem.

This study covers the following objectives:

1. Perform hydraulic reliability analysis of water distribution systems under stochastic conditions.
2. Apply EPANIT method for generating model input data.
3. Develop a methodology for calculating system reliability based on developed criteria and compare the results.
4. Study of final results to see the effect of stochasticity of random variables on nodal and system reliability.

IV. LITERATURE REVIEW

Wong and Yeh (2002) [10] present a systematic approach for solving the management problem of a contaminated groundwater supply system. They selected supply water quality criteria based on stochastic health risk assessment and concluded with the establishment of a trade-off relationship between the increased management cost and the desired level of protection. They performed uncertainty analysis by using Gaussian quadrature numerical integration as an alternative to the nested Monte Carlo simulation.

They adopted two management approaches - treating the contaminated groundwater with granular activated carbon and using imported water to lower the contamination level in the water supply. They used a random hydraulic conductivity field to produce the contamination variability at each extraction well. They obtained a trade-off relationship between the increased management cost and the level of protection by performing the uncertainty analysis at several supply water quality criteria for each of the two management approaches.

V. EXPERIMENTS

The town of Bani Walid is located on 150-km. southeast from Tripoli consisting of narrow urban-center zone and suburban settlements. Urban center (rather compact) is located at the tableland between 250 and 270 m.a.s.l. In immediate proximity of the town the wadi cuts-in in the direction west east. Said wadi spread in the valley 200 to 350 m. wide, at 175 to 230 m.a.s.l. At both wadi sides there are suburban – rural settlements extending towards tableland, left and right of wadi. According to map obtained for that area it can be seen that there are 13 rural settlements, which can be adopted as individual urban entities.

Population in the town of Bani Walid is about 39,000 people while in the villages it is about 40,000 people. Due to lack of more precise data regarding both area and population, it was adopted that all villages are the same, with approximate population of about, 3080 people. for the Detailed Design Document, the same approach was adopted.

VI. SELECTION OF HYDRAULIC PARAMETERS 5

The hydraulic calculation was made based on the following criterions:

As concern distribution pipelines, ductile iron pipes – class "k9" are adopted. The flow resistance was calculated according to D'Arcy-Weisbach equation and friction coefficient according to Colebrook-White equation.

As concern the roughness coefficient, "k" value of 0.5; was used in calculations of water supply system. There are 13 rural settlements, which can be adopted as individual urban entities.

A. CALCULATION OF REQUIRED WATER QUANTITY5 –

According to data, required water quantity is as follows:

- Population (town of Bani Walid) N = 39,000
  Population (suburban total) N = 40,000
- Specific water consumption
- qspec. = 250 L/inhabitant/day
- From adopted parameters – population and specific consumption of water, the following water requirement was calculated:
- town of Bani Walid qmax.daily = 39,000* = 112.85 L/s
- suburban settlements qmax.daily = 40,000* = 115.75 L/s
- i.e. as per one settlement qmax.daily = 115.75/13 = 8.90 l/s

Total water quantity required for water supply of town and settlements is as follows:

Qmax.daily = 112.85 + 115.75 = 228.50 L/s

Taking into the consideration the conditions for connections prescribed (daily design flow capacity per one connection not exceeding): Qavailable = 22,500 m3/day), the specific available water quantity reached the capacity of:

Qavailable = 22,500/86,400 = 260.40 L/s

From ratio between available and required water quantity, it can be seen that there is the reserve of about 15% that can be used by the consumers within the town of Bani Walid.

HYDRAULIC MODE5

At the Hydraulic Model Layout basic hydraulic model of the system in matter, having the following markings of the system facilities and elements:

Major system's storage facility is newly-designed reservoir Bani Walid

(R-BW) storage chambers bottom level is 295.00 m.a.s.l.

Existing town elevated storage tank Al Markaz capacity is V = 300 m3

Adopted material of distribution pipes is ductile cast iron (DI)

Length of suburban storage feeder pipelines (DN300 - for supply of local tanks) were estimated to 1000 m.

The system of water supply is so designed to enable maximal use of the reservoir Bani Walid (R-BW) storage reservoir hydraulic grade, i.e. to enable the supply of as bigger as possible number of consumers using gravity pressure. This assumption performed necessary base for determination of required piezometric levels at which the sub-urban tanks should be located in order to provide required water quantity. This quantity is given at the level of "maximal daily consumption rate" and in the day of maximal consumption it reaches.

for the town of Bani-Walid qmax design = 112.85 L/s =113 L/s

qmax design = 8.90 L/s = 9 L/s

- for villages (per one villag) DWT Decomposition model

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Table.2 Tank characteristics of hypothetical water distribution network

Tank 1		**Tank 2**	
Base Elevation	295	Base Elevation	258
Min Elevation	0	Min Elevation	26
Initial Elevation	5.5	Initial Elevation	29
Max Elevation	6	Max Elevation	30
Tank Diamer	50	Tank Diameter	10

Availability is evaluated in terms of developing the required average pressure. Pressures between 15 m and 50 m are considered to be desirable pressures under normal daily demands.
The minimum cut-set can be defined as "a set of system components (e.g., pipes) which, when failed, causes failure of the system". However, system failure will not occur if any component of the set does not fail.
Assuming that a pipe break can be isolated from the rest of the system, the minimum cut-sets are determined by closing a pipe or combination of pipes in the water distribution system and using a hydraulic simulation model to determine the values of pressure head at each demand node of the system. In this study, EPANET was used.
By comparing these pressure heads with the minimum pressure head requirements, the reliability model can determine whether or not this pipe or combination of pipes is a minimum cut-set of the system or an individual demand node. A minimum cut-set for a node is the one that causes reduced hydraulic availability at that node, while a minimum cut-set for the system is a cut-set that reduces the hydraulic availability for any node in the system.

DEMAND RELIABILITY

This part of the Reliability Analysis module doesn't make any corrections in node demands but only calculates system reliability and amount of undelivered water due to pressure drop below the minimum pressure15 m or pressure increase above the maximum pressure 50 m. The performance is evaluated with respect to the time period during which threshold values (Hmax and Hmin) are not satisfied. For each node the threshold values are defined and the failure frequency evaluated. The reliability is calculated according to equation:
$R_i = 1 - f_i$
Where Ri – reliability at node. fi – failure frequency at node
$0 \leq (f_i = \Sigma t_i / T) \leq 1$
Where ti – total failure time. T – total time period of simulation
The method of calculation of total failure time and total time period is presented in the Fig 5.1.1 below.

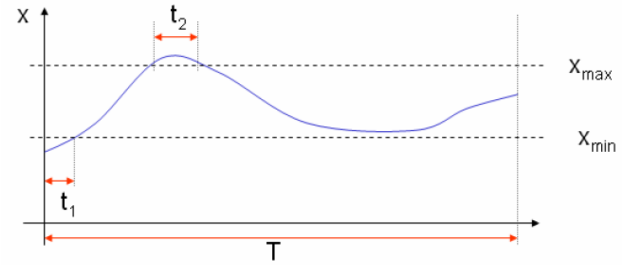

Fig. 2. Watermark embedding algorithm Block Diagram

In the Fig 5.1. X max and X min are maximum and minimum limits for the pressure in the system.
Time periods t1 and t2 are periods when the real pressure exceeds the limiting values and ti=t1+t2 is total failure time (Ingeduld P., 2003) (9).
In this method of calculation, it is considered that water is undelivered to customer in two cases: pressure at a node is below the minimum or above the maximum. Pressure increase above the upper limit doesn't cause a demand drop; it only increases the risk of failure in the node. Probably it was the only way to express the situation when any of the pressure threshold values are not satisfied in terms of undelivered water.

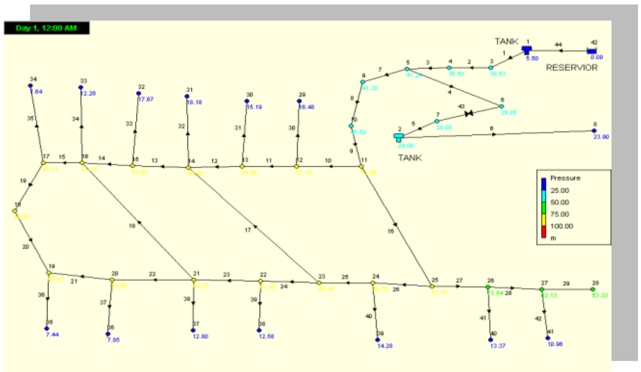

Fig. 3. Main water distribution network

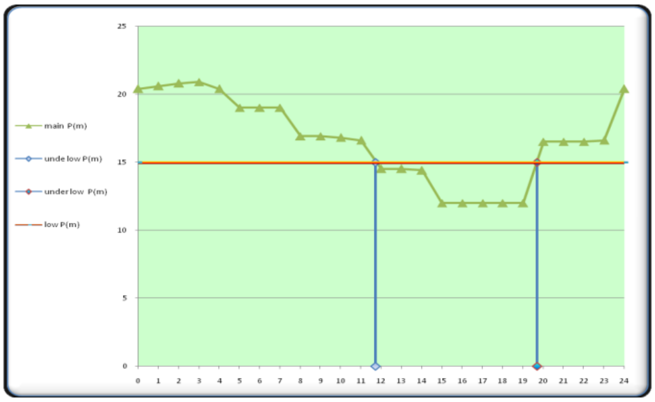

Fig. 4. Pressure for nod 29 for main water distribution network

Reliability for nod 29:

Σ t29=8 hours

T = 24 hours

F29 = Σ t29 / T = 8/24=0.333

R 29 = 1− f 29 = 1- 0.333=0.666

R 29 =0.666*100 = 66.6%

Table.2 Tank characteristics of hypothetical water distribution network

Time period	12-4 AM	4-8 AM	8-12 AM	12-4 PM	4-8 PM	8-12PM
multiplier	0.8	0.9	1	1.1	1.2	1

(A) Time Pattern

Nod	**Reliability**	**Nod**	**Reliability**
29	0.666	36	0.166
30	0.666	37	0.333
31	0.666	38	0.166
32	0.666	39	0.333
33	0.333	40	0.166
34	0.166	41	0.166
35	0.166		
Average		0.359	

(B) NODS RELIABILITY

The average reliability for all distribution nodes is 0.359*100= 35.9% and this result is low in spite of, without calculating demand for fire hydrant.

In another hand we see in case of cutting one pipe in the network loop this cause to fail all the system sometimes as we see in the following cassis.

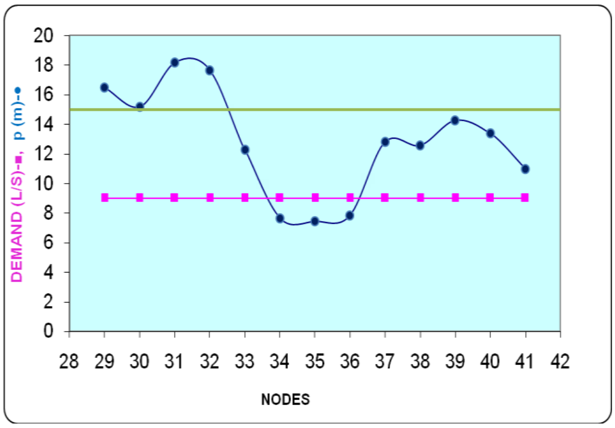

Fig. 5. Profile of pressure (m), demand l/s for main water distribution nodes

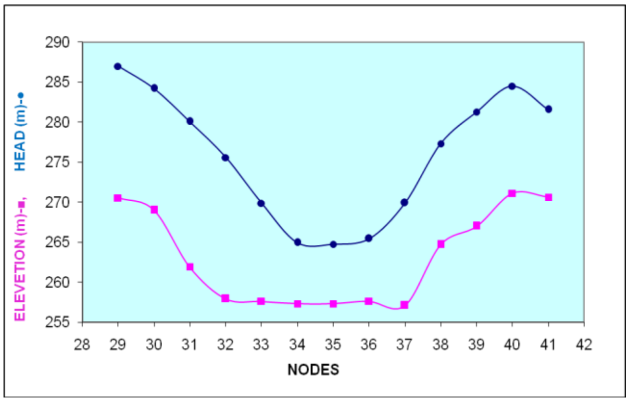

Fig. 6. Elevation, head (m) for main water distribution nodes

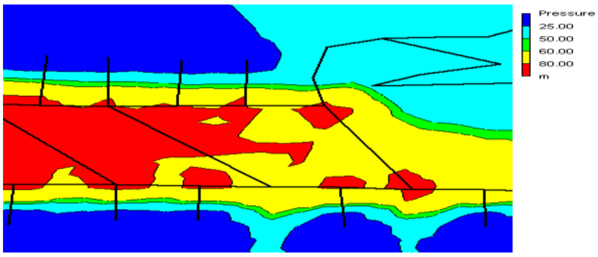

Fig. 7. Contour plot- pressure for main water distribution network

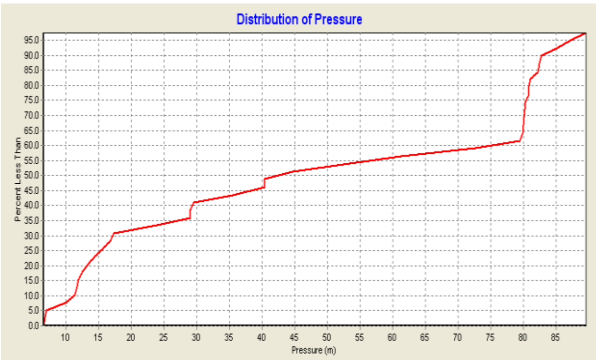

Fig. 8. Distribution of pressure for the main network

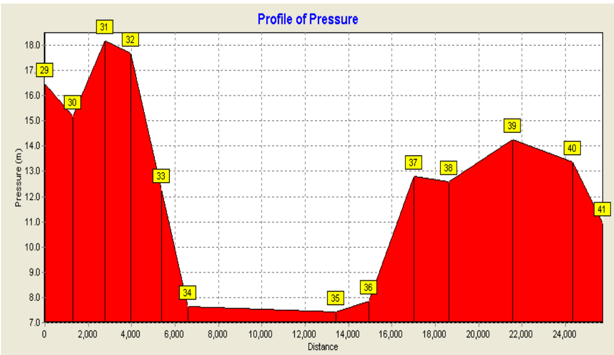

Fig. 9. Profile of pressure for main distribution nodes (29-41)

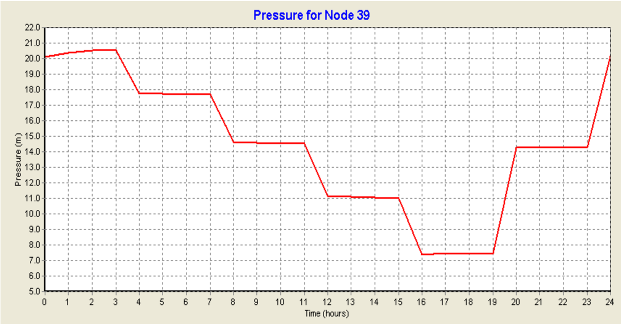

Fig. 10. Profile pressure for main distribution node 39

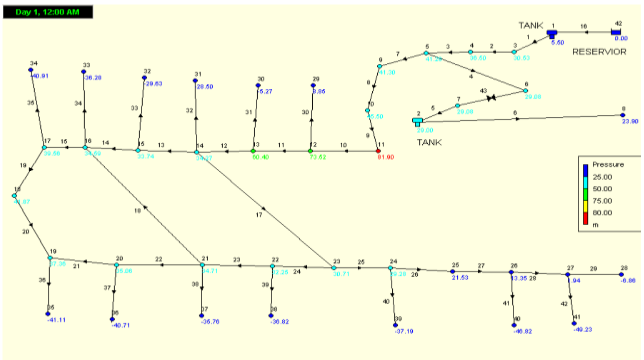

Fig. 11. Water distribution network (Variant 1)

In the variant we suggest occurring cutting in pipe No 16, we see the system all are failed except nod Jo 29 its pressure is 8.85 although it's pressure less than minimum pressure required (15)m, as we see in the pressure chart in fig 5.1.10 below.

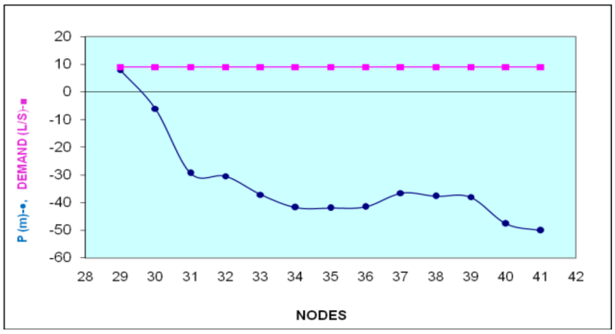

Fig. 12. pressure (m) for distribution nodes (variant 1)

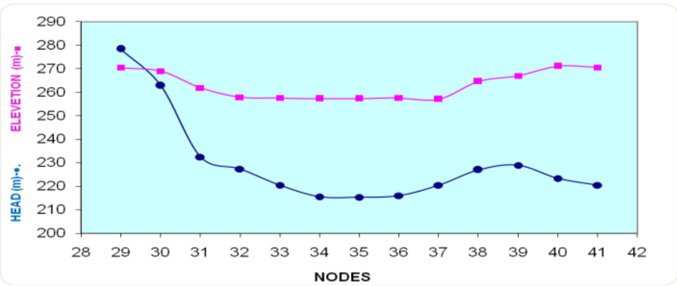

Fig. 13. Head, elevation (m) for distribution nodes (variant 1)

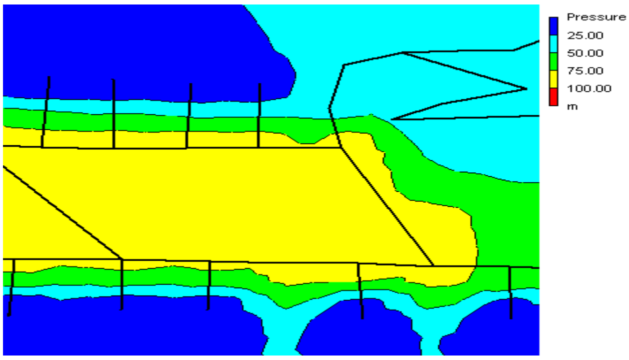

Fig. 14. Contour plot- pressure for distribution nodes (variant 3)

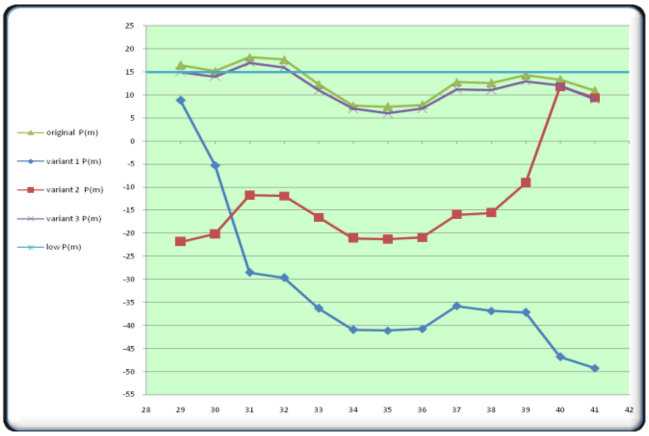

Fig. 15. Pressure (m), for distribution nodes (main, variant 1,2, 3)

VII. CONCLUSIONS SUMMARY

The main purpose of this research was to calculate the hydraulic reliability of a water distribution system which requires extensive planning and maintenance in order to ensure that it will provide consumers with safe water in adequate amounts at all times. Hydraulic reliability of water networks comprises junction and system reliability; therefore, reliable networks should fulfill the average pressure head requirements between (15-50) m at all the distribution junctions of the network so that consumers can meet their water demands.

The calculated system reliability values for BANI WALID Water Distribution System is 35.9 %, which means that the pressure at all junctions of the BANI WALID network will be not distributed to all nods in all time at the average pressure requirements. In addition to the higher pipe failure rates, the reason of low reliability value of BANI WALID network is the selection of low mean pressure. If the mean pressure in BANI WALID network were increased from 15 m, then the system reliability value would increase.

The judgment of the acceptable system reliability values of BANI WALID network can be made by looking at the complaints related to lower pressures of supplied water coming from consumers. For instance, if it is observed that there are complaints of low pressures from consumers residing in a particular area covering 30% of the water distribution system; this means that the pressures at this particular area are not meeting the minimum pressure requirements, therefore the probability of the minimum pressure requirements at all the junctions of the water distribution system are fulfilled would be 70%.

After performing the hydraulic simulation of BANI WALID regarding the water Distribution System, it was found that the main cause of low reliability values of BANI WALID network is lower pressures & the failure of main pipes which are connected directly to the reservoirs and tanks.

Therefore, in order to improve the reliability, it is necessary to provide precautionary measures by providing alternative pipes leading to the sources so that in case of failure these alternate pipes could be used immediately. It is also suggested to properly maintain the pipes which are directly connected to the reservoirs and tanks and if necessary, they should be replaced. The actual finding and results of this research can contribute greatly in assessing the hydraulic reliability of water distribution methods by EPANET program, it will help the municipalities, Water and Rural Affairs, and Water Authorities, to set guidelines for establishing reliability levels with respect to the pressure head requirements of the consumers that would be useful for satisfying the water requirements of the consumers, as presently there are no proper guidelines available in the literature to establish the reliability levels.

VIII. RECOMMENDATIONS FOR FUTURE WORK

Based on this research, the following recommendations are made:

- A Law needs to be promulgated to set the hydraulic reliability levels of the water distribution system in all the metropolitan cities. In order to establish reliability levels, a "Code of Reliability Levels" needs to be developed by the consensus of the water and municipal authorities of the cities. After developing the "Code of Reliability Levels", water authorities should be made responsible for implementing the code and monitoring the reliability levels of their respective water distribution systems.
- It is suggested that in all the metropolitan cities, data regarding water distribution systems such as pipe break data, pipe repair and replacement costs, etc, should be documented properly, so that it can be easily accessible and available to the concerned authorities.
- Extension of the developed model is suggested in future by generating model input data by assuming different probability distributions other than normal distribution. Moreover, other random variables e.g. pump efficiency; can be considered to investigate their effects on the hydraulic reliability of the water distribution system.
- The developed model must be converted in the form of software using Graphical User Interface to merge the developed codes with the hydraulic simulation software, i.e. EPANET, WATER CAD for easy use by the engineers and operators in the field.
- By taking the procedures properly we can get the following utilities.
- reducing the number of maintenance operations, after reducing the operating pressure of the system;
- Easy finding the most vulnerable areas of the network;
- Making quick maintenance and repair in the network.

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