VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

BRNO UNIVERSITY OF TECHNOLOGY

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RISK ANALYSIS FOR INTERMITTENT WATER SUPPLY SYSTEMS

Analýza rizik vodovodů s přerušovanou dodávkou vody

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Short Version of PhD Thesis

Study Field Water Management and Water Structures

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Opponents

Presentation date:

Brno, Czech Republic

Keywords

Drinking-water supply; FTA; HAZOP; Hazard; Intermittent water supply; Low pressure; Probability; Risk analysis and Risk.

Klíčová slova

Zásobování pitnou vodou; FTA; HAZOP, Nebezpečí; Systémy s přerušovanou dodávkou vody; Nízký provozní tlak; Pravděpodobnost ; Analýza rizik a Rizika.

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1 INTRODUCTION

The available surface and ground water sources throughout the world are becoming depleted or polluted; this problem is aggravated by the rate of increasing in populations, rapid urbanization, and increasing in domestic, public, and industrial water demand, the previous problems make it difficult to supply water systems with sufficient quantity of water with acceptable quality, especially in developing countries where is no sufficient technical, financial and/or technological ability to find out new water sources, desalinate available sea water or to treat the available raw water.

There are two major views on how insufficient water sources problem should be considered; the first view looks at a transfer to 24-hour supply by reducing water loss and adding new supply sources, while the other accepts intermittent supply as a reality (1).

Intermittent water supply (IWS) strategy is to provide water to the distribution network less than 24 hours a day and/or less than 7 days a week

In some developing countries, due to financial and technological constraints it is not practically possible to operate water supply systems for twenty-four hours a day even if the water is available, so the water utilities transfer the operation from continuous into intermittent strategy.

In IWS systems, the consumers depend on individual roof and /or ground storage tanks to provide their daily needs of water for domestic, industrial, and other uses. This means that the consumption of water is not necessarily provided from the network directly, but may be provided from the storage system, in this case the consumption of water is not restricted only by the pressure that is available in the distribution network, but also they are restricted by the capacity of the storage tanks.

IWS system is a distribution system with unstable hydraulic conditions (2),

1. The distribution network is not fully pressurized pipeline network but a network with very low pressures,
2. It is a network with restricted water supply hours per day,
3. Inequitable distribution of the available water,
4. Thousands of roof tank connections,
5. Associated with high level of water contamination,
6. In case of fire, unavailable immediate supply.
7. Meter malfunctioning and
8. Inconvenience to consumers.

1.1 Objectives of the thesis

A number of studies were carried out to describe IWS systems, identify and estimate the health risks of such a kind of systems for humans, study the water quality and the contamination problems, and to suggest approaches and combinations of software programs to model IWS networks.

In Institute of Municipal Water Management / BUT Czech Republic, WaterRisk project was carried out during 2006-2010; Risk Analysis methodology and software tool were set to identify, assess, and rank the weaknesses and shortcomings of an existing water supply system as a first step of risk management of that system, continuous water supply systems are considered under this methodology and the intermittent water supply was inserted as an Undesired Event (UE) in the Undesired Events list (3).

The first objective of the thesis is to develop risk analysis methodology to handle with IWS systems in developing countries conditions that includes undesired events identification; risk estimation, risk evaluation and reduction plan.

The second objective is to implement the developed methodology on one potential undesired event, the studied UE in the thesis is UE_ Low operational pressure, which was chosen because of its high effect on the other failures and problems in the system, low pressure may occur because of the high rate of water withdraw from a limited capacity network in a short period, so hydrodynamic operational pressure will decrease under its designed values or because of low supplied pressure in main transmission.

2 THE STATE OF THE ART

This section presents the definition of an Intermittent Water Supply (IWS), gives an overview of the history of the studies and researches that carried out in its field, it also outlines the used techniques and methods in this research.

2.1 Overview of Intermittent Water Supply (IWS)

Drinking water supply systems are designed and operated with continuous pattern for twenty-four hours a day and seven days a week to cover customers water demand, firefighting system demand, in developing countries it is not practically possible to operate drinking water systems as a continuous pattern, due to many reasons (4) such as insufficient quantity of the water sources, unacceptable quality of available water, financial, technical and/or technological problems in the system.

Rationing in general is the controlled distribution of scarce resources, goods, or services. Rationing controls the size of the ration, the allowed portion of the resources being distributed on a particular day or at a particular time, rationing of food and water may become necessary

Water rationing called Intermittent Water Supply (IWS) Fig.1. Generally, a period of eight hours or less is considered adequate to supply the network with drinking water.

IWS strategy can vary according to season in some countries; in Damascus for example the frequent interruptions in water supply particularly occur in summer.

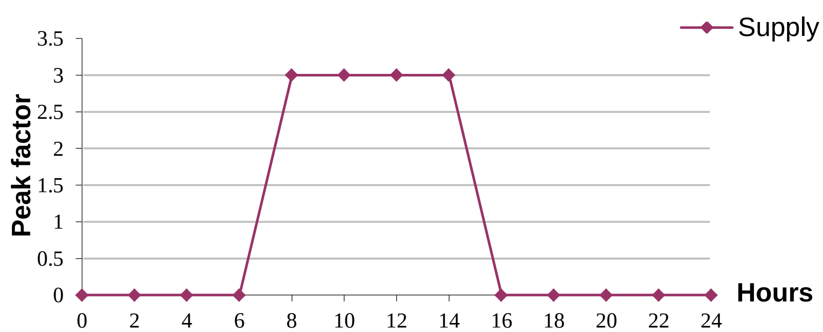

Fig 1 IWS pattern

Only in developing countries, IWS strategy is acceptable while in developed countries it is not acceptable so that it is considered as an UE that relate to distribution system's section in the catalogue of UEs under WaterRisk project in Czech Republic, 2010 (3); only temporary emergency interruption in supply is allowed.

In Latin America and the Caribbean (PAHO & WHO 2001), it is estimated that 60% of the population is served by household connections having intermittent service.

In Africa and Asia (WHO and UNICEF 2000), it is estimated that more than one-third and one-half of urban water supplies, respectively, operate intermittently.

An intermittent supply has been associated with increased water use and wastage compared with a continuous supply, wastage occurs because taps are left on owing to inconsistency or lack of predictability of when the next water supply will arrive, and thus each household attempts to draw a maximum quantity during supply hours (5).

A comparison between performance of water distribution systems during intermittent versus during continuous was studied for four Indian cities during 2007, both water modes were studied to collect data about water consumption, pressures at various points in the network, flow rate and variation, total flow into the network and water quality (6).

In other different Indian zones, nearly all (90–100%) samples were negative for fecal coliforms during continuous service, while only 24–73% was negative during intermittent supply (7).

Interrupted service has also been linked to a number of disease outbreaks in the developing world, in Jakarta, Indonesia, poor reliability of the water supply was most strongly associated with diarrheal illness (8).

In Beirut, a study was conducted over an eight-month period, during which samples were collected from household tanks and drinking water taps of Beirut's network, the study shows that IWS seriously affects water quality due to the potential suction of non-potable water by negative pressures, biofilm detachment, and microbial re-growth especially when static conditions occur; also it focused on storage tanks which often encourage bacterial re-growth (9), (10).

To model IWS systems, Cabrera and Tyatchkov (1) proposed method to use known free public domain network models, such as SWMM for modeling initial pipe network charging and EPANET for modeling the intermittent distribution network with roof tanks.

In other study, EPANET source code was adjusted to allow for modeling pressure dependent demands, for dealing with low pressure and “dry pipe” situations. A configurable tool was developed for incorporating roof tanks into the water supply analysis and for better formulation and schematization of the system hydraulics (2)

IWS‘s previous studies and researches lack any direct study considering risk analysis

2.2 Discussion of used methods in risk estimation in the research

HAZOP; FTA; Dempster-Shafer theory and Monte-Carlo method were employed in this research for probabilities analysis purpose

2.2.1 HAZard OPerability Analysis technique (HAZOP)

HAZOP technique is a Process Hazard Analysis (PHA) technique used worldwide for studying not only the hazards of a system, but also its operability problems, by exploring the effects of any deviations from design conditions. (11); (12)

HAZOP technique was developed in the early 1970s at Imperial Chemical Industries (ICI) in UK (13).

Many authors attempted to extend the HAZOP application from identifying hazards to evaluate their impacts, HAZOP and FTA considered as the best PHA combination of techniques to do so (14)

Bendixen (15) confirmed that HAZOP-FTA combination was the most effective way to identify, quantify, and control risks. They believed that HAZOP is the most versatile technique for hazard identification in new and existing facilities, and that FTA is the most appropriate hazard-quantification technique.

Nolan (11) provided in his publication guidance to HAZOP (Hazard and Operability) and What-If review teams associated with the petroleum, petrochemical and chemical industries.

Pátkai (16) considered the need for a data-management tool for aiding the HAZOP process. He justified the tools and methods by generating more structured data, and collecting it for additional developments.

HAZOP analysis process is executed in three phases definition phase, preparation phase and examination phase (17)

The performance of study is depending on many factors such as: duration of study, proper planning and management of study schedule, team content, number of team members, and experience of team leader and participation of team members (18)

2.2.2 Fault Tree Analysis (FTA)

FTA is a deductive system analysis (from general to specific) to identify various ways that a system failure or accident may occur, it is a logic diagram that displays the interrelationships between a potential “critical” event in a system and the causes of this event (19)

Ericson (20) provided in his paper an overview on the historical aspects of the Fault Tree Analysis, the paper includes important developments on FTA through the years, improvements in the process and contributions.

FTA was originally developed in 1962 at Bell Laboratories by H.A. Watson, in connection with a U.S. Air Force Ballistics Systems Division contract to evaluate the Minuteman Launch Control System (20)

In Sweden, fault tree analysis was used on an integrated level of a large drinking water system to develop a method for integrated and probabilistic risk analysis of entire drinking water systems; the analysis included situations where no water is delivered to the consumer (quantity failure) and situations where water is delivered but does not comply with water quality standards (quality failure), then the applicability of Customer Minutes Lost (CML) as a measure of risk was evaluated as the rest of the study (21)

Fault tree should be constructed due to the circumstances of the actual system instead of being fitted to actual data, then when hard data is missing or insufficient, expert judgments must be used (21)

2.2.3 Dempster-Shafer theory

DS theory is approach to express uncertain judgments of experts; it allows coping with absence of preference, due to limitations of the available information, which results in indeterminacy. Its calculus describes the subjective viewpoint as an assessment for an unknown objective fact (22)

DS-Evidence theory was first proposed by Dempster (1967, 1968) and later extended by Shafer (1976). This theory is also called Dempster–Shafer theory (DST) (23)

In DS theory, frame of discernment Ω is defined as a set of mutually exclusive elements that allow having a total of 2^{Ω} subsets in a power set (P), where Ω is the cardinality of a frame of discernment. For example, if Ω = {T, F}, then the power set (P) includes four subsets, i.e., {ø (a null set), {T}, {F}, and {T, F}}.

Applying Dempster-Shafer Theory to FTA can help modeling uncertainties with less effort as shown by Guth, he discusses Ω= {h1, h2, h3} ≡ {“event occurs”, “uncertain”, “event does not occur”}. (24)

DS Theory depends on belief structure and Estimate Value (Bet) to interpret the outcome probability of event, belief structure represents a continuous interval [belief (Bel), plausibility (Pl)] in which true probability may lie, (25)

2.2.4 Monte Carlo method

MC method could be used to generate a database of studied parameter in the project, Monte Carlo simulation can be performed to fulfill the missing values (if any) in the original database, as it provides flexibility, manage the uncertainty and even provide more accurate results than simple descriptive statistics (e.g. the average value).

Monte Carlo method (MC) was invented in 1946 by Stanislaw Ulam, a Polish born mathematician, MC provides approximate solutions for many mathematical problems by generating random numbers and calculating what fraction of the numbers obey some property or properties; it consists of a performance of a simulation using random numbers to determine the future behavior of a random variable.

In practice, it is difficult and expensive to obtain precise estimates of event probability because in a majority of cases these estimates are the result of an expert’s limited knowledge, incomplete information, poor quality data or imperfect interpretation of a failure mechanism, these unavoidable issues impart uncertainties in the ETA and make the entire risk analysis process less credible for decision making (25)

To describe uncertainties in input data (i.e., event likelihood) and propagate them through ETA, probability-based approaches such as Monte Carlo simulations (MCS) have been traditionally used (Bae et al., 2004). This approach requires sufficient empirical information to derive probability density functions (PDFs) of the input data, which are generally not available (Wilcox and Ayyub, 2003), As an alternative to objective data, expert knowledge/judgment is used, especially when the data collection is either difficult or very expensive (Rosqvist, 2003) (25)

3 BASIC STRUCTURE OF THE METHODOLOGY

3.1 Description of studied IWS system

The studied system is designed and modeled as continuous water supply then operated as intermittent water supply because of changes in circumstances such in Damascus water supply network; each customer node (Flat or house) is provided with storage system to store water during supply hours and use it during interruption hours, each storage system consists of tanks and water pumping system Fig.2.

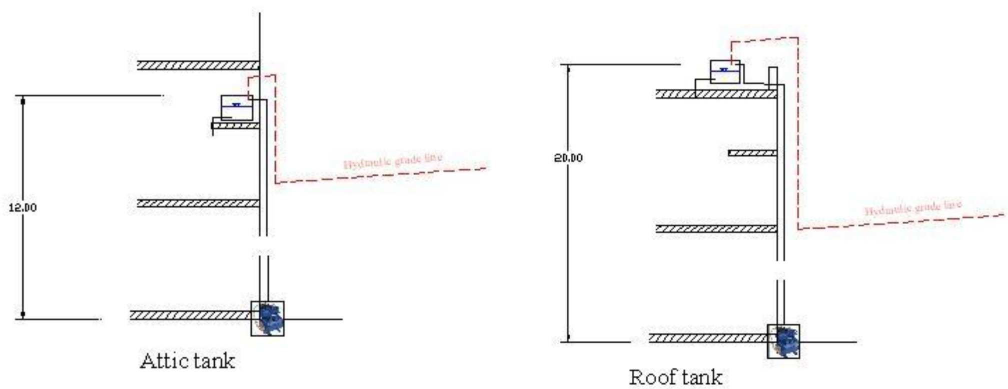

Fig. 2 Attic and roof water storage tanks

3.2 Risk Analysis Methodology for IWS systems

For intermittent water supply system, Fig.3 illustrates the generic framework of Risk Analysis Methodology.

It distinguishes between two different cases of the methodology; Simple Risk Analysis Methodology (SRAM) and Complex Risk Analysis Methodology (CRAM) which differ in Probability analysis procedures, Fig.4

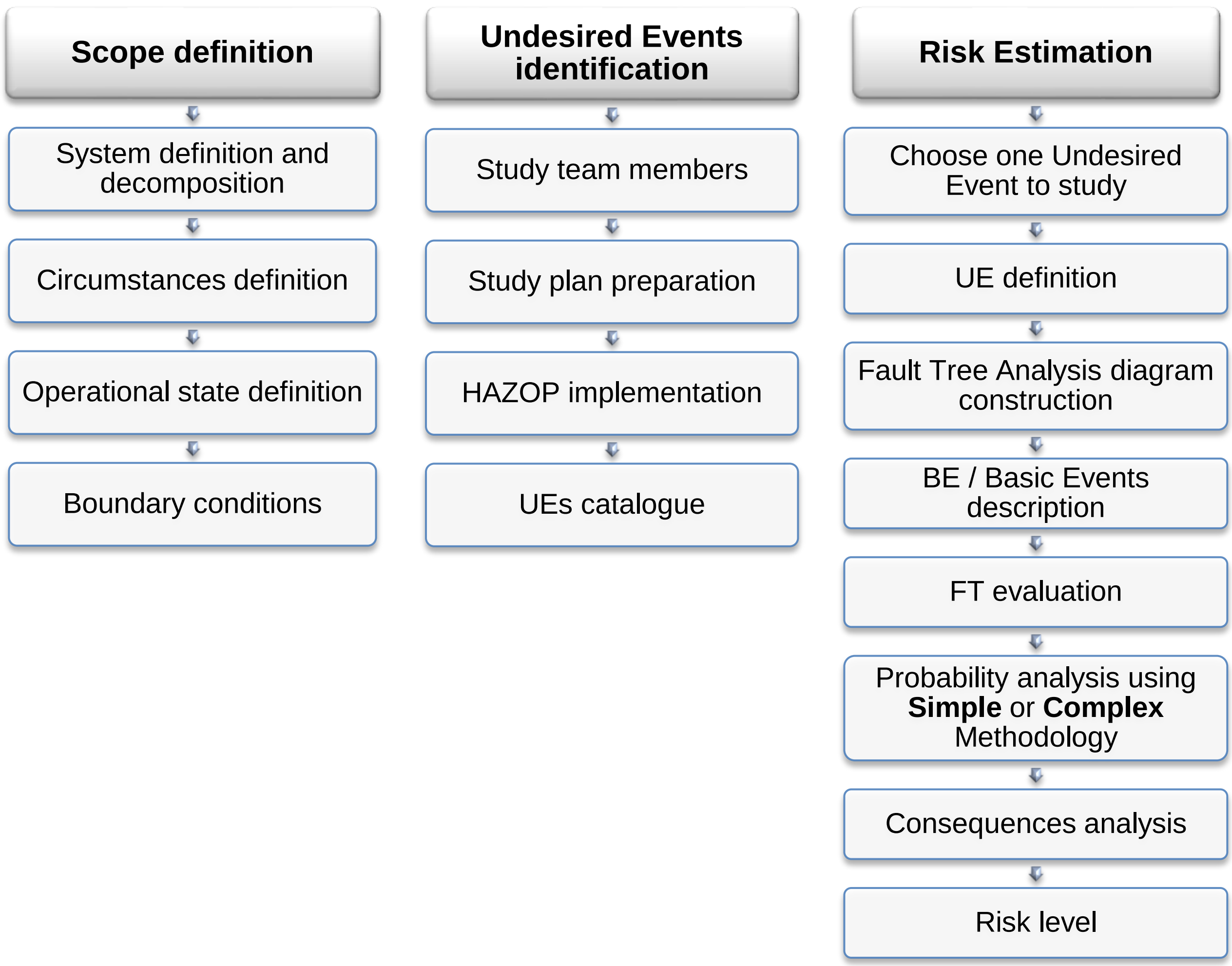

Fig. 3 Generic framework of Risk Analysis Methodology for IWS systems

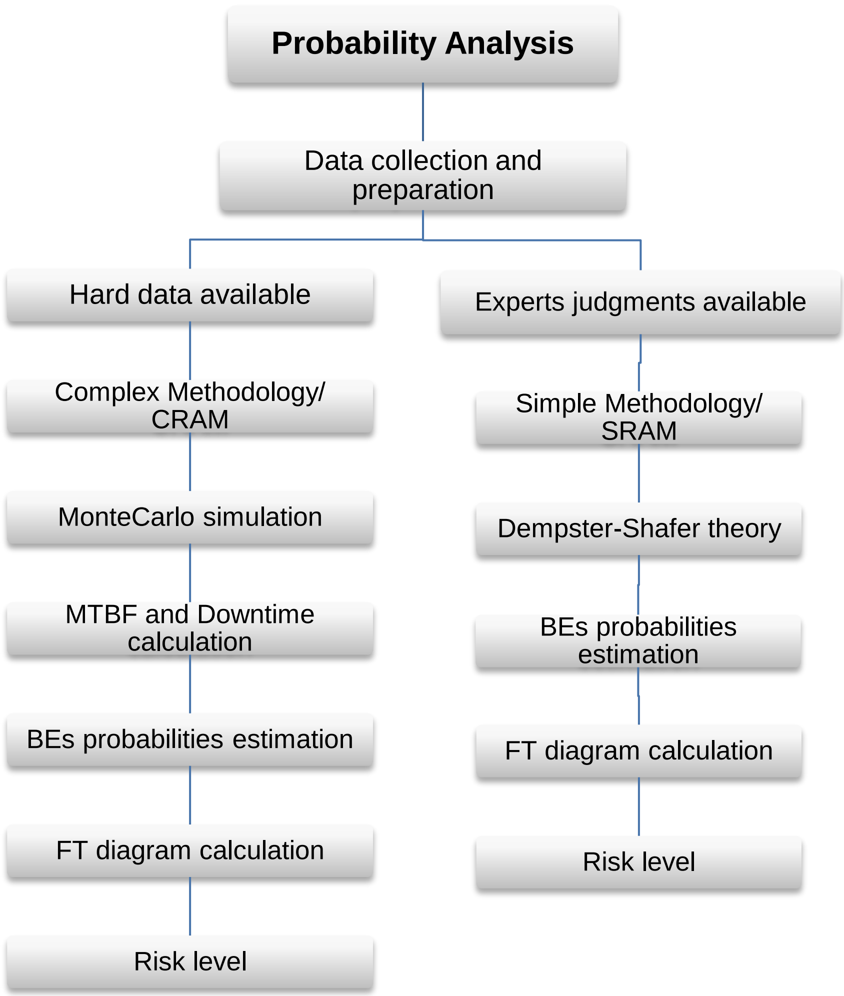

Fig. 4 Probability Analysis under Simple and Complex Methodology

Hard data are measurement, records, reports and statistics, for example:

- Operational records: supply pattern, customers' meters and billing records, pressure records, known problems, control and monitors methods.
- Operational diary: information of the frequency of electrical power cut and records of failures.
- Maintenance, repairs and cleaning plan: maintenance frequency and procedures, documentation of implemented maintenance plan, cleaning works plan, and duration of repairs.
- Records of failures: pipelines, valves, technological and technical failures.
- Information about the end-users (consumers)

3.3 Undesired Events identification

UEs identification considers quality, operational, technical and technological UEs that may happen in the system and financial, healthy and social UEs that may impact the customers;

For potential UEs identification process and catalogue list setting, the proposed methodology employed HAZard and Operability (HAZOP) technique.

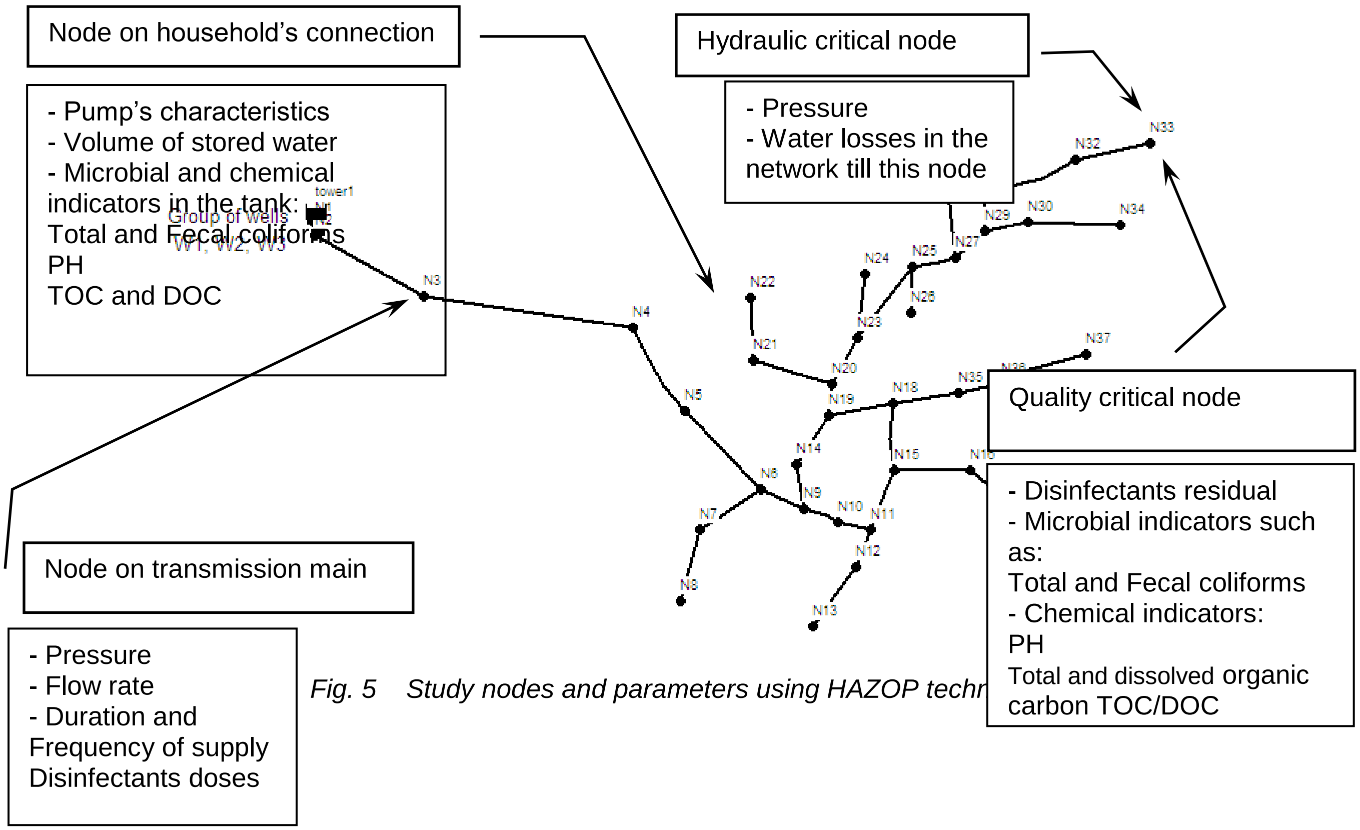

Fig. 5 Study nodes and parameters using HAZOP techn

All HAZOP tables are depending on reading, brain storming, discussions with water utility's experts, and academic information; they are not depending on a real case study, all documents are presented in the full version of the thesis.

In a real case study some modifications could be taken into account, for example:

- We may change or add new study nodes according to the available data
- We may add or delete some parameters according to the available data
- We may add more guide words or use other criteria to determine the deviations of the system from standard operating conditions.

3.3.1 Undesired Events catalogue list

As a result of HAZOP implementation, the catalogue list of the potential UEs has been defined:

UE 1_ Low operational pressure,

UE 2_ Interruption in water supply,

UE 3_ Inadequate hydraulic capacity of the network,

UE 4_ Troubles in fire-fighting systems,

UE 5_ Ingress of contaminated ground water or sewage water into the network,

UE 6_ Deterioration of microbiological parameters of the distributed water,

UE 7_ Deterioration of microbiological parameters of water in storage tanks and cisterns,

UE 8_ Biofilm production,

UE 9_ Biofilm detachment event,

UE 10_ High doses of disinfectants,

UE 11_ THMs and other disinfection's by-products Production,

UE 12_ Unacceptable turbidity values of the distributed water,

UE 13_ Deterioration in taste, smell, or temperature of the distributed water,

UE 14_ Corrosion the inner surface of the pipelines,

UE 15_ Increasing in water losses,

UE 16_ Equipment, meters, and valves failure,

UE 17_ Breaks and cracks in the pipelines,

UE 18_ Financial pressure on the customers,

UE 19_ Health risk for customers

3.4 Risk estimation for UE_ Low operational pressure

The methodology of risk estimation for one of UE (Low operational pressure) is presented in this chapter as an example.

Low pressure in IWS systems has high effect on the other problems, it causes meter malfunctioning, failure in firefighting systems, water contamination and it forces the consumers to use individual household pumping systems to be able to reach the water during supply period.

Fault Tree analysis is normally carried out in the following steps:

1. System and boundary conditions definition
2. Top event selection: UE_ Low operational pressure (Top event).
3. FT diagram construction

All immediate, necessary and sufficient causes are numbered and sequenced in the order of occurrence and then are used for drawing or constructing FT diagram based on AND and OR gates.

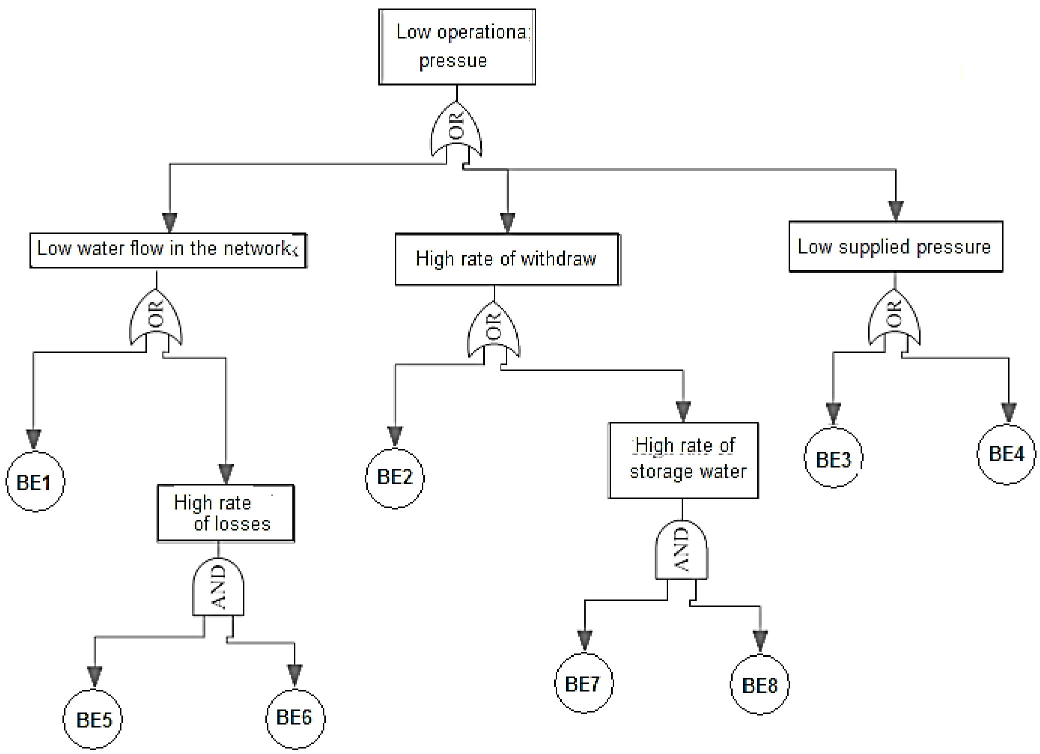

Fig. 6 Schematic fault tree for UE_ Low operational pressure in IWS system

4. FT Evaluation

Evaluation process is to identify minimal cut sets, compute the probabilities and risk rate.

The OR-gate is equivalent to the Boolean symbol "+", and the AND-gate is equivalent to the Boolean symbol "."

$$E_1 \text{ OR } E_2 = E_1 + E_2 = E_1 \cup E_2 \quad 1$$

$$E_1 \text{ and } E_2 = E_1 \cdot E_2 = E_1 \cap E_2 \quad 2$$

Where E_1, E_2 are events

To simplify FT diagram, all basic events are considered independent, and the diagram can always be translated into an equivalent set of Boolean equations, thus an understanding of the rules of Boolean algebra contributes materially toward the construction and simplification of fault trees (26)

Minimal cut set for the proposed fault tree diagram in general case, Fig.6;

$$T = OR_2 + OR_3 + OR_4$$

$$= BE_1 + AND_1 + BE_2 + AND_2 + BE_3 + BE_4$$

$$= BE_1 + (BE_5.\mathrm{BE}_6) + BE_2 + (BE_7.\mathrm{BE}_8) + BE_3 + \mathrm{BE}_4$$

$$= M_1 + M_2 + M_3 + M_4 + M_5 + M_6 \qquad 3$$

Where: T is the top event (UE) M_k is a minimal cut set,

Each minimal cut set consists of a combination of specific component failures E_i (Basic events) Equ.4

$$M_k = E_1 \,.E_2 .. E_n \qquad 4$$

The probability equation is reduced into rare event approximation:

$$P(TOP) = P(M_1 + M_2 + M_3 + \cdots + M_n = \sum_{i=1}^{n} P(M_i) \qquad 5$$

Or we use minimal cut set upper bound

$$P(TOP) = 1 - \prod_{i=1}^{n}(1 - P(M_i)) = 1 - [(1 - P(M_1)).(1 - P(M_2)) \dots .(1 - P(M_i))] \qquad 6$$

To calculate the probability of top event according to general case of tree, Equ.3

$$P(TOP) = 1 - \prod_{I=1}^{n}(1 - P(M_i))$$

$$P(TOP) = 1 - [\big(1 - P(M_1)\big)\big(1 - P(M_2)\big) * \big(1 - P(M_3)\big) * \big(1 - P(M_4)\big) * \big(1 - P(M_5)\big) * \big(1 - P(M_6)\big)]$$

$$P(TOP) = 1 - [\big(1 - P(BE_1)\big).(1 - [P(BE_5).P(BE_6)]).\big(1 - P(BE_2)\big).(1 - [P(BE_7).P(BE_8)]).\big(1 - P(BE_3)\big).(1 - P(BE_4)] \qquad 7$$

3.4.1 Probability analysis

To calculate probability of top event $P(TOP)$, the probabilities of basic events $P(BE_i)$ are required

$$P(BE_i) = \lambda.t/(1 + \lambda.t) \qquad 8$$

$$\lambda = 1/MTBF \qquad 9$$

Where λ is an event failure rate (1/hour) t is exposure time or repair time (hour)

MTBF is the Mean Time between Failures (hour)

3.4.1.1 Basic events analysis under Complex Methodology

Data is available:

1. Specify variable for the BE,
2. According to available data we can choose the appropriate probability distribution (density function $f(t)$) for each BE_i and estimate required parameters,
3. Use the estimated parameters to generate random values of the variable by applying Monte Carlo simulation (with iteration 10,000) using excel worksheets,
4. Define a critical value and the failure condition
5. Define the time step between values [hours], for this case study Step= 1 day = 24 hours
6. Binary encode the available data [1 represent Y which means the failure occur, 0 represent N which means the failure is not occur]
7. Calculate MTBF the mean time between failures

$$MTBF = average(TBF)$$

$$TBF = Step * n \quad (10)$$

Where n is the number of 0 codes between two sequential 1 codes

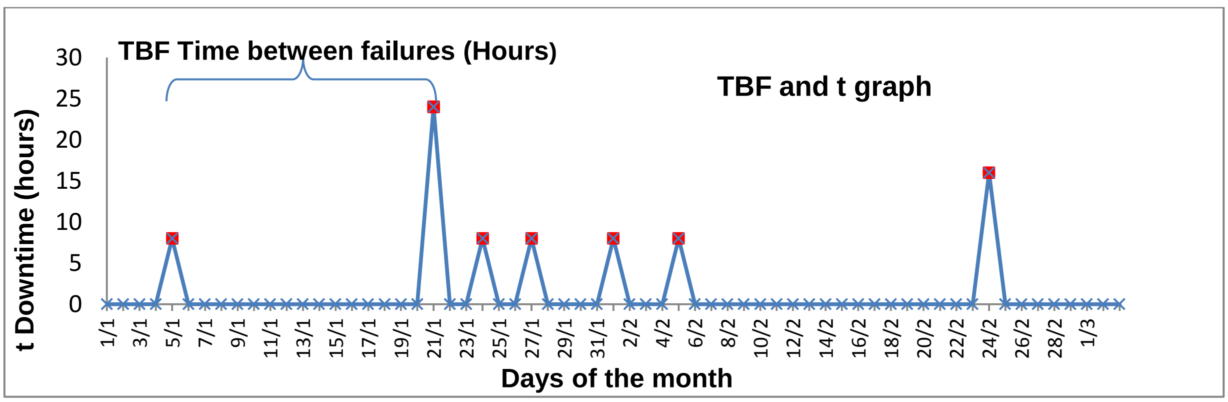

Fig. 7 TBF and t graph

8. Calculate average t the exposure time (downtime) using the equation Equ.11

$$t = Step * ration * m \quad (11)$$

Where $Step * ration$ is the number of supply hours, which could be 4, 8 or 12 hours

m is the number of 1 code between two sequential 0 codes

9. Calculate probability Equ.8

3.4.1.2 Basic events analysis under Simple Methodology

NO data available:

1. Estimate the probabilities under uncertainty using Dempster-Shafer theory that depending on experts judgments (Data sources)
2. Two **independent** data sources m_1 and m_2 are adequate in this project to estimate belief mass $m(p_i)$ for each subset which is proportion of knowledge to every subset,
3. For the basic event BE_i we have frame of discernment $\{\mathrm{Y}, \mathrm{N}\}$, Y represents the occurrence of the failure and N represents non-occurrence of the failure; the power set P includes four subsets {{ø}, {Y}, {N}, {Y, N}}
4. Belief mass could be estimated according to many methods and approaches depending on each data source, in this case study I followed the steps:
    - Each data source estimates MTBF and t according to its experiences, available data, statics and historical records or any other information about the network,
    - Calculate belief mass $m_1(Y) and\ m_2(Y)$ using Equ.12
    - Estimate $m_1(N)\ and\ m_2(N)$
    - Calculate $m_1(Y,N)\ and\ m_2(Y,N)$

$$m_i(Y,N) = 1 - [m_i(Y) + m_i(N)] \qquad 12$$

5. Calculate the values $m_{1-2}(Y)$, $m_{1-2}(N)$ and $m_{1-2}(Y,N)$, according to combination rules, I used Yager combination rules because it handles with the conflict between data sources if there is any.
6. Arrange the calculations in a table as follows :

Table 1 Table of DS Theory calculation

	m_2	{Y}	{N}	{Y,N}
m_1		$m_2(Y)$	$m_2(N)$	$m_2(Y,N)$
{Y}	$m_1(Y)$	$m_1(Y)\times m_2(Y)$	$m_1(Y)\times m_2(N)$	$m_1(Y)\times m_2(Y,N)$
{N}	$m_1(N)$	$m_1(N)\times m_2(Y)$	$m_1(N)\times m_2(N)$	$m_1(N)\times m_2(Y,N)$
{Y,N}	$m_1(Y,N)$	$m_1(Y,N)\times m_2(Y)$	$m_1(Y,N)\times m_2(N)$	$m_1(Y,N)\times m_2(Y,N)$
$\sum m_1(p_a).m_2(p_b)$				
m_{1-2} (combination rules)				

7. Calculate the Estimate Value $Bet(Y)$ Equ.13 which is equal to the estimated probability value of occurrence

$$P_i(BE_i) = Bet(Y) = \frac{m_{1-2}(\{Y\})}{1} + \frac{m_{1-2}(\{Y,N\})}{2} \qquad 13$$

3.4.2 Risk level

Risk level is estimated in terms of Customer Minutes Lost (CML). CML has previously been used in the drinking water sector; CML is a measure that corresponds to the number of minutes per year the average consumer is affected by failure (21).

Since it is not meaningful to estimate the number of people affected for the top event in the fault tree, it was estimated at a lower level for n different main types of minimal cut sets, Equ.14

$$R = \sum_{i=1}^{n} P(M_i).C_i \qquad 14$$

Where $P(M_i)$ is the probability of the minimal cut set i

Ci is the number of consumers affected.

4 CASE STUDY

In this case study we will evaluate the proposed methodology in the thesis Chapter.3, the study will be implemented on a supposed water system, the system is not real but it simulates real systems in Damasus suburbs/ Syria, the simulation is applied on the operational strategy; rationing plan; the general situation of the system and the consumers and the senarios of storing and bringing water from private sources.

Simulated network was designed as a continuous with average age 50 years, it was operated as a continuous for about 10 years then latter ,when the quantity of water sources is insufficient, it was operated as an intermittent according to a specific rationing plan to control the available quantity of water; the household storage system is provided for each building node in the system.

Total demand covers 55% residential demand; 30% commercial demand and 15% public demand, small size of a municipality is 10000 inhabitants, with average water demand 110 liter/day/person.

Total annual drinking water production amount is about 346000 m^3 equivalents to 95 liter/day/person which is less than average water demand

The drinking water supply system is constructed by pumping the water from main water source to a water tower, the drinking water then is distributed to the town from the tower by gravity through pipes that made from steel, PVC and cast iron with diameters range from 25, 80 to 110 mm, and total length of pipe about 50 km

The main source of water for the town is a group of wells W1, W2 and W3, where it is permitted to take annual an amount of water allowed by:

W1 $Q_{max.y}$ =166 000 m^3, W2 $Q_{max.y}$ =70 000 m^3, W3 $Q_{max.y}$ =110 000 m^3

Water from the wells is healthy and secure chlorinated, the used disinfection agents are chlorine and chlorine dioxide, Disinfection with chlorine has the advantage of efficiency and durability and that keep good residual disinfectant concentration in the water, which can prevent contamination of the water supply system by means of pathogens or microorganisms, in the same time water utility tries to control certain factors that influence the production of DBPs such as: the amount of disinfectants, the amount of organic material or minerals present during disinfection; temperature; PH and reaction time.

The temperature of the water getting out from the well is between 10 to 16° C

To reduce corrosion of metal distribution pipes the pH is adjusted to 8

Laboratory analyses are regular carried out at several points such as the wells and the main pipeline

The distribution network is approximately 50 km in length and pipe material consists of steel (45% from the pipelines network), PVC (40%) and ductile iron (15%).

The network is supplied with water from a water tower, to ensure sufficient pressure in areas; water tower is constructed with a total volume of 1200 m^3.

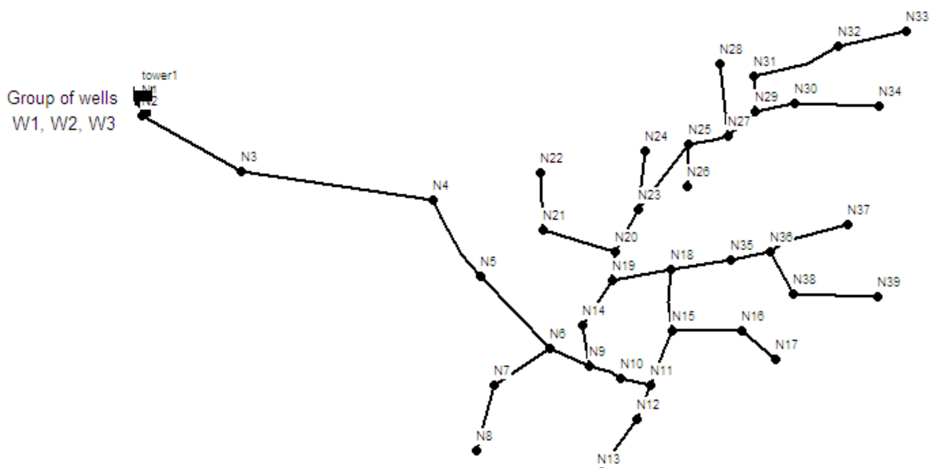

Fig. 8 Water distribution network scheme

The pressure at the consumers tap has to be in the range of 200 up to 500 kPa (2 up to 5 bars).

Minimum allowed pressure in the water main is 100 kPa and the maximum pressure is 700 kPa

Pipe corrosion and external loads are common reasons to pipe bursts and breaks that cause water leakage.

Cleaning of water tower carried out by a hired company and once every 2 years

Operational state of the system, the distribution network is supplied with water eight hours a day, and seven days a week because of insufficient quantity of the water sources Fig.1

4.1.1 Complex Methodology outputs

I analyzed daily data for 18 months, some of them were missed so I employed Monte Carlo method to generate random values of studied variables, the used probabilities distribution in the study were Normal distribution for (Supply values, demand values) and Bernoulli for (technical failure, electrical failure).

The full calculations of the case study exist on a CD, it is available upon request.

As an example of calculations, I present the following tables of BE1

Table 2 Part table of MTBF and average t calculation and the outputs

	Critical value	1100 m3/day	
Water production (m3/day) (m3/day)	**Binary code**	**TBF/Time between failures (hours)**	**t / Downtime (hours)**
1500	0	-	-
1524	0	-	-
947	1	48	-
1405	0	-	24
1219	0	-	-
1060	1	48	-
1272	0	-	24
1218	0	-	-
1656	0	-	-
1240	0	-	-
1359	0	-	-
1196	0	-	-
1463	0	-	-
1361	0	-	-
1388	0	-	-
1077	1	216	-
980	1	-	-
1324	0	-	48
1402	0	-	-
1300	0	-	-
1250	0	-	-
1026	1	48	-
1385	0	-	24

Outputs	
MTBF (hour)	118
λ=1/MTBF (1/hour)	0.008
average t (hour)	10
PROBABILITY	0.076

Table 3 Probabilities values of the Basic Events according to CRAM

calculated value

P(BEi)	
BE1	0.076
BE2	0.107
BE3	0.056
BE4	0.070
BE5	0.066
BE6	0.072
BE7	0.115
BE8	0.200

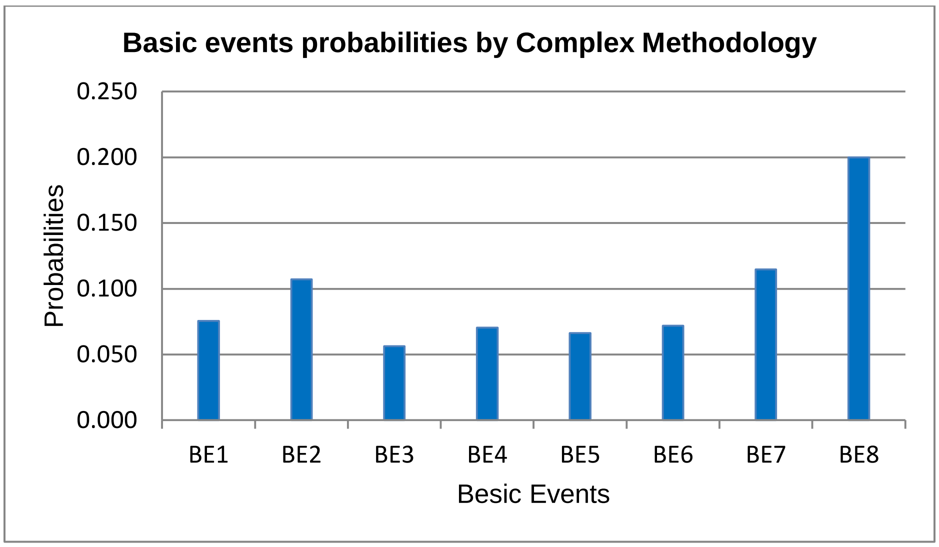

Fig. 9 Basic events probabilities by CRAM

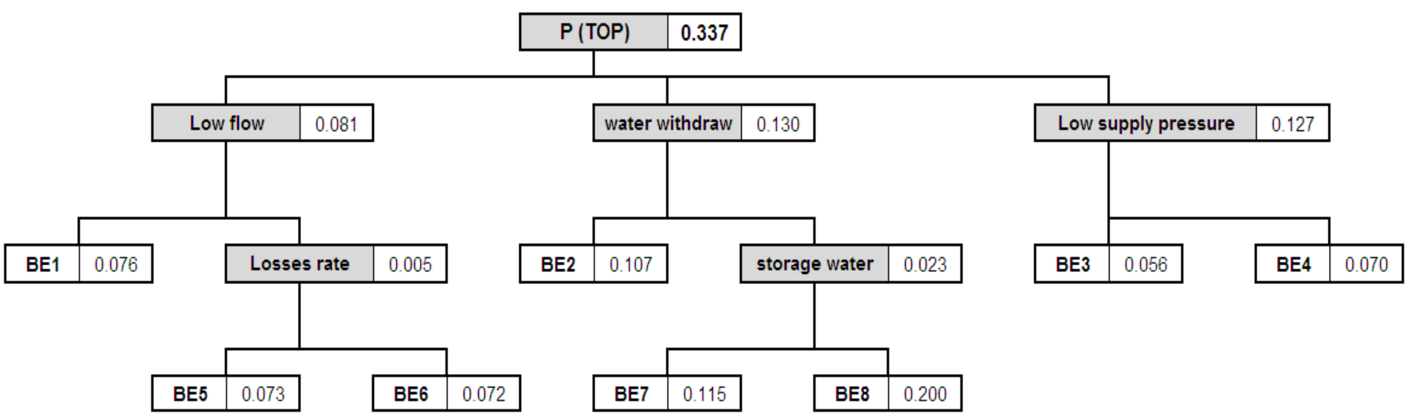

Fig. 10 Fault tree calculation under SRAM using Equ.5

Table 4 P(top) and risk level calculations under CRAM

Min. cutsets		P(Mi)	1-P(Mi)	Ci (person)
M1	BE1	0.076	0.924	7000
M2	BE5,BE6	0.005	0.995	5000
M3	BE2	0.107	0.893	6000
M4	BE7,BE8	0.023	0.977	7000
M5	BE3	0.056	0.944	4000
M6	BE4	0.070	0.930	10000
P(TOP) Equ.32		0.296		
Risk level (Minutes)		2287		

$$R = (0.076 * 7000) + (0.005 * 5000) + (0.107 * 6000) + (0.023 * 7000) + (0.056 * 4000) + (0.070 * 10000)$$

$$R = 2287 \text{ min}$$

That means 38 hours and 7 minutes during the year each consumer will have an interruption supply because of Low pressure problem, and if we consider 8 supply hours per day that means 4.8 days without water for each average consumer per year.

4.1.2 Simple Methodology outputs

Data process under SRAM, as an example of the calculations I present the following table of BE1

Table 5 Data sources assumptions

Data sources assumptions			
	MTBF (hour)	λ (1/hour) Equ.35	t (hour)
m1	100	0.010	6
m2	150	0.007	10

Belief mass calculation Equ.34	
m1 {Y}	0.057
m2 {Y}	0.063

m1 (Data source 1)	
m1 {Y}	0.057
m1 {N}	0.750
m1 {Y,N}	0.193

m2 (Data source 2)	
m2 {Y}	0.063
m2 {N}	0.800
m2 {Y,N}	0.138

Table 6 Calculations and outputs with DS theory

	m2	{Y}	{N}	{Y,N}
m1		0.063	0.800	0.138
{Y}	0.057	0.004	0.045	0.008
{N}	0.750	0.047	0.600	0.103
{Y,N}	0.193	0.012	0.155	0.027
∑m1(pi).m2(pi)		0.023	0.858	0.027
Yager combination rules		0.023	0.858	0.119
k (the degree of conflict)		0.092		
Bet(BEi) {P(Bei)}		0.083		
Bel(BEi) {Min.}		0.023		
Pl(BEi) {Max.}		0.142		

Table 7 Belief, estimate value and Plausibility of the basic events

	Min. Bel(BEi)	Expected Bet(BEi)	Max. Pl(BEi)
BE1	0.023	0.083	0.142
BE2	0.033	0.103	0.174
BE3	0.020	0.075	0.131
BE4	0.027	0.088	0.149
BE5	0.025	0.084	0.143
BE6	0.024	0.084	0.144
BE7	0.038	0.133	0.227
BE8	0.034	0.208	0.381

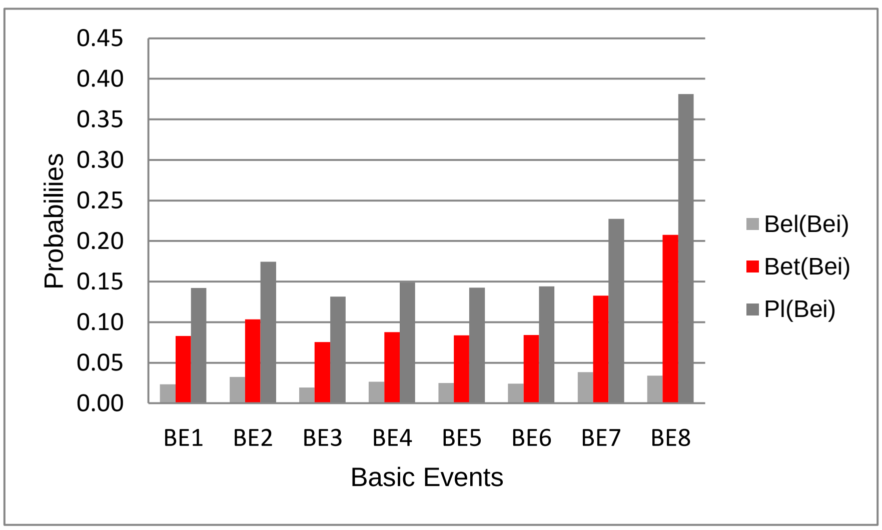

Fig. 11 Belief, estimate value and Plausibility of the basic events

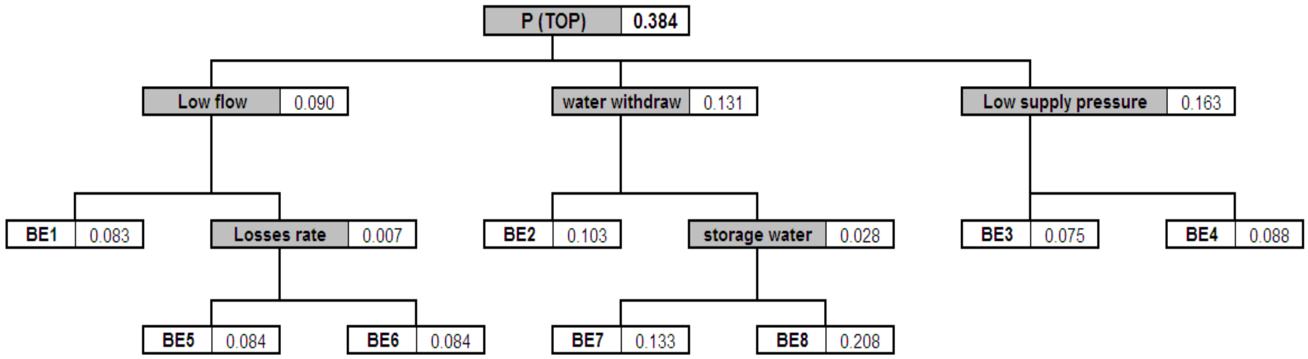

Fig. 12 Fault tree calculation under SRAM using Equ.5

Table 8 P(top) and risk level calculations under SRAM

Min. cutsets		P(Mi)	1-P(Mi)	Ci (person)
M1	BE1	0.083	0.917	7000
M2	BE5,BE6	0.007	0.993	5000
M3	BE2	0.103	0.897	6000
M4	BE7,BE8	0.028	0.972	7000
M5	BE3	0.075	0.925	4000
M6	BE4	0.088	0.912	10000
P(TOP) Equ.32		0.330		
Risk level (Minutes)		2608		

$$R = (0.0828 * 7000) + (0.00706 * 5000) + (0.1035 * 6000) + (0.0276 * 7000) + (0.0755 * 4000) + (0.0878 * 10000)$$

$$R = 2608 \text{ min}$$

That means 43 hours and 28 minutes during the year each consumer will have an interruption supply because of Low pressure problem, and if we consider 8 supply hours per day that means 5.4 days without water for each average consumer per year.

5 CONCLUSION

Nowadays, IWS strategy is widely prevailed in developing countries especially in the Middle East. Its unique hydraulic behavior, its supply pattern, and the period and frequency of supply make IWS systems full with deviations from the designed operating conditions.

The study outputs are presented in UEs catalogue list and Risk Analysis Methodology.

The main characteristics of proposed methodology:

- Applicable and easy to implement
- Adaptable with any kind of IWS system and open for any modifications or changes in system conditions

- Support decision making system, and suggest applicable risk reduction options and strategies
- Distinguish between simple and complex probability analysis procedures
- Uncertainty of the inputs is a measure of accuracy of the outputs
- It may give outputs with acceptable accuracy (CRAM) or it may give indication of the risk level of the system (SRAM)
- The proposed methodology implemented on a simulated IWS system case study.

HAZOP technique was a good choice to build up the UEs list because it is:

- Effective and clear,
- Comprehensive
- Flexible
- A perfect tool to manage and arrange the team work step by step
- Exploring almost all possible deviations and problems that may occur in the system
- Employing HAZID (HAZard Identification) techniques such as Brainstorming, checklist and what- if analysis under schematic productive plan.

FTA technique was used to estimate the probabilities of occurrence and consequences and then to estimate risk levels.

FTA and HAZOP are the best PHA combination of techniques to identify hazards and evaluate their impacts.

The solutions are always depending on the economic situations of the countries, if the country doesn’t have enough budget to treat withdraw water from other sources or manage water loss, so it’s necessary to look for technical solutions to manage and optimize the existing water source and networks, and control water demand by set higher tariff and billing,.

Low pressure in IWS systems has high effect on the other problems, it causes meter malfunctioning, failure in firefighting systems, water contamination and it forces the consumers to use individual household pumping systems to be able to reach the water during supply period.

The study is considered the first step in risk analysis for IWS systems field which many other studies may branch out from it.

Comparison between different existing types of IWS system should be carried out to achieve more UEs by applying HAZOP.

The rest of UEs from the catalogue need to be analyzed to estimate the risk levels

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Abstract

Intermitted Water Supply strategy is implemented commonly in some developing countries nowadays in order to minimize the water scarcity problems. Unstable hydraulic conditions in the distribution system, low pressure, high risk of water contamination, wasting water, rising costs paid by consumers and water providers, failures and problems with consumption metering and inconvenience to consumers are some of the consequences.

Risk Analysis Methodology is developed to handle with intermittent water supply systems in developing countries conditions that include undesired events identification; risk estimation and risk evaluation and reduction plan, the catalogue list of potential undesired events (UE) which may occur in these types of systems have been also developed using the HAZard and OPerability technique (HAZOP).

The developed methodology is implemented and tested in this research on one of the potential undesired events *UE _ Low operational pressure*