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FAKULTA STAVEBNÍ
ÚSTAV VODNÍHO HOSPODÁŘSTVÍ OBCÍ

FACULTY OF CIVIL ENGINEERING
DEPARTMENT OF MUNICIPAL WATER MANAGEMENT

RISK ANALYSIS FOR INTERMITTENT WATER SUPPLY SYSTEMS

Analýza rizik vodovodů s přerušovanou dodávkou vody

Ph.D THESIS

Téze Disertační Práce

AUTHOR Ing. MZAYAN ALAYOUBI

Autor Práce

SUPERVISOR Doc. Ing. LADISLAV TUHOVČÁK, Csc

Vedoucí Práce

Brno, Czech Republic

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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*

Abstrakt

Systémy s přerušovanou dodávkou vody jsou dnes běžně realizovány v některých rozvojových zemích a to z důvodu minimalizace problémů způsobených nedostatkem vody. Proměnlivé hydraulické podmínky v distribučních systémech, nízké tlaky, vysoké riziko kontaminace, plýtvání vodou, nárůst cen, které platí spotřebitelé a poskytovatelé vody, poruchy a problémy při měření spotřeby vody a nepříjemnosti pro spotřebitele s tím spojené, to jsou některé důsledky provozování takovýchto systémů. Za použití Studie nebezpečí a provozuschopnosti HAZOP (HAZard and OPerability technique) byla vyvinuta metodika rizikové analýzy pro systémy s přerušovanou dodávkou vody a byl vytvořen katalogový seznam potenciálních nežádoucích stavů (NS), které mohou nastat v systému tohoto typu. V této práci je také popsáno použití rozvinuté metodiky a Analýzy stromu poruchových stavů FTA (Fault Tree Analysis), která je použita k analýze pravděpodobností a důsledků včetně ohodnocení stupně rizika s nejistotou pro jeden z nežádoucích stavů NS_Nízký provozní tlak

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1 INTRODUCTION

The purpose of a Water Supply System (WSS) is to make water available to customers with at least acceptable pressure, flow, continuity and water quality.

WSS consists of the following main sub-systems:

1. Water sources, which could be

1.1 Surface water sources and/or

1.2 Ground water sources

2. Treatment plant

3. Water distribution system, which generally consists of

3.1 Main water tank (reservoir);

3.2 Transmission mains;

3.3 Pumping system;

3.4 Water supply network

Usually, drinking water supply systems are designed and operated on continuous pattern for twenty-four hours a day and seven days a week, continuous water system (CWS).

Any sub-system quantity failures i.e. no water is delivered to the consumers or quality failures i.e. water is delivered but unfit for human consumption according to water quality standards, may cause system supply failure, in developing countries frequent interruption in water supply is acceptable while in developed countries only temporary emergency interruption in water supply is allowed.

1.1 Statement of the problem

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).

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, generally a period of eight hours or less is considered adequate to supply, so the water utilities transfer the operation from continuous into intermittent strategy.

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, most water distribution systems all around the world are designed and modeled with continuous supply pattern then the water utilities may transfer it into intermittent due to the constraints and problems that are mentioned before, IWS strategy is acceptable in most of the developing countries and is not acceptable in the developed countries.

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.

From the hydraulic point of view, when the consumers are using the water from their roof tanks, they are disconnected from the distribution system, and two independent patterns can be distinguished in this case:

The first pattern is at the consumer's tap which is actually a consumption pattern.

The second pattern is at the tank which is actually a filling pattern,

Intermittent water supply system (IWS) 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.

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.

Because of the zero or low pressure in IWS network, there are two types of backflow that may occur. The first is back-siphon age, which occurs when the pressure drops sufficiently to cause a vacuum effect in the pipe, which can then draw in contaminants through leaks in the pipes or through cross-connections which are any connections between a potable drinking water supply and a non-potable, undesirable, polluted or contaminated source (3)

1.2 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 (4).

The first objective of the thesis is to develop risk analysis methodology to handle with intermittent water supply 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.

- Undesired event (UE) 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.

According to HAZOP technique, we divided the studied subsystem into four study nodes, for each node we determined parameters, indicators and guide words to prepare HAZOP documents, draw the possible scenarios and then set the potential undesired events that may occur in the system by determining the deviations from standard operating conditions, the documents were set depending on reading, brain storming, discussions with experts and on academic and theoretical information.

- Risk estimation

It is the estimation procedures of the probabilities of occurrence, the consequences and the risk levels for each UE in the system under uncertainty

For risk estimation, Fault Tree Analysis (FTA) technique with specific criteria was employed.

FTA's diagram displays the interrelationships between a potential top event in a system and the causes of this event (Basic events). A properly constructed fault tree provides a good illustration of the various combinations of (component) technical failures, human errors, normal events, and environmental factors that may result in a critical event for the system (5).

Fault tree should be constructed due to 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 (6)

We should consider entire system from source to tap during analysis because of

1. Interactions between subsystems
2. Failure maybe compensated by other subsystem

I used FTA to analyze probabilities under uncertainty and then to estimate risk level for undesired event.

Probabilities estimation for FTA diagram were modeled and performed with Monte-Carlo simulation in the case of available hard data, and by Dempster-Shafer theory (evidence theory) depending on experts' judgments and knowledge in the case of unavailable hard data.

- Risk evaluation and Risk reduction:

It determines the acceptable risk levels and suggest measures and risk reduction options by changing and affecting in the potential causes of the UE in two ways: hard measures (control and mitigation) and soft measures (regulations & policies).

1.3 Thesis outline

The thesis is organized into the following main chapters:

- State of the Art outlines the researches that carried out about IWS systems, presents the limitations and gaps in these researches and reviews the used methods and techniques in the thesis to analyze and estimate risk levels in IWS systems. Chapter 2
- Basic structure of the proposed methodology that presents the theoretical foundations and principles to understand and deal with risk analysis in intermittent water supply systems in developing countries conditions. Chapter 3
- Case Study describes the implementation of the theoretical methodology that we detailed in chapter 3 on a simulated case study. Chapter 4
- Conclusions and discussions summarize research observations. Chapter 5

2 THE STATE OF THE ART

This section presents the definition of an Intermittent Water Supply (IWS), gives an overview of the state of the art and the history of the studies and researches that carried out in its field.

It also outlines the most familiar water risk projects; undesired events identification techniques, risk level estimation methods and then it gives more details about the used techniques 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 (7):

- Insufficient quantity of the water sources,
- Unacceptable quality of available water,
- Financial problems or
- 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 during an emergency, such as a natural disaster or during wars. The Federal Emergency Management Agency (FEMA) has established guidelines for civilians on rationing food and water supplies. According to FEMA standards (8), every person should have a minimum of one quart (1 liter) per day of water, and more for children, nursing mothers, and the ill.

The governments in developing countries have put in place an emergency strategy because of one or more of the previous mentioned reasons, so they rationing their energy and/or water sources, each country has its particular rationing plan according to specific case, for example the Jordanian government reduces the amount of water pumped to households: water would be rationed with each house getting it once or twice a week, for three to five hours at a time.

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.

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

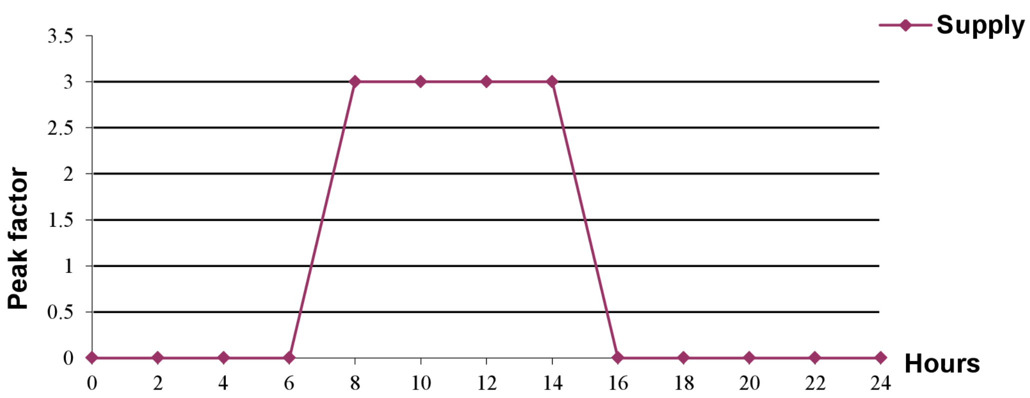


Fig 1 IWS pattern

IWS system is a distribution system with unstable hydraulic conditions, it is not fully pressurized pipeline network but a network with very low pressures, with restricted water supply hours per day, thousands of roof tank connections, high possibilities of water contamination, meter malfunctioning and inconvenience to consumers (2).

From hydraulic behavior side, continuous water distribution network is normally “demand-driven “network, while intermittent network is “supply-driven” and “pressure-driven” network (1).

The complexity in intermittent supply and pressure contributes in distribution system failures and decrease health status.

In IWS systems, the consumers depend on individual roof and /or ground storage tanks to provide their daily needs of water for domestic uses and depend on household pumps to meet the required pressure. During non-supply hours, pipes are empty and polluted water enters into the pipelines at vulnerable spots then water becomes contaminated and large doses of chlorine or other disinfectants are required to make water safe from microbial pollution. The valves suffer wear and tear, inconvenient supply hours affect poor people, large size of storage is required and so many other failures are been met (9).

We can clearly notice that the daily water supply cannot meet the daily water demand Fig .2.

Hourly water demand:

$$Q_H = Q_{H.avg} \cdot P_{f.h} \quad (1)$$

Where

Q_H is the flow in a specific time (l/hour);

$P_{f.h}$ is the hourly peak factor;

$Q_{H.avg}$ is the average hourly flow in the water system (l/hour)

$$Q_{H.avg} = q \cdot n \quad (2)$$

where

q is the average demand rate per person (l/hour/person)

n is the number of customers (person)

In Syria for instance, the average demand rate $q \cong 2 - 6.7$ l/hour/person, and the average daily consumption is between 50 – 160 l/day/person.

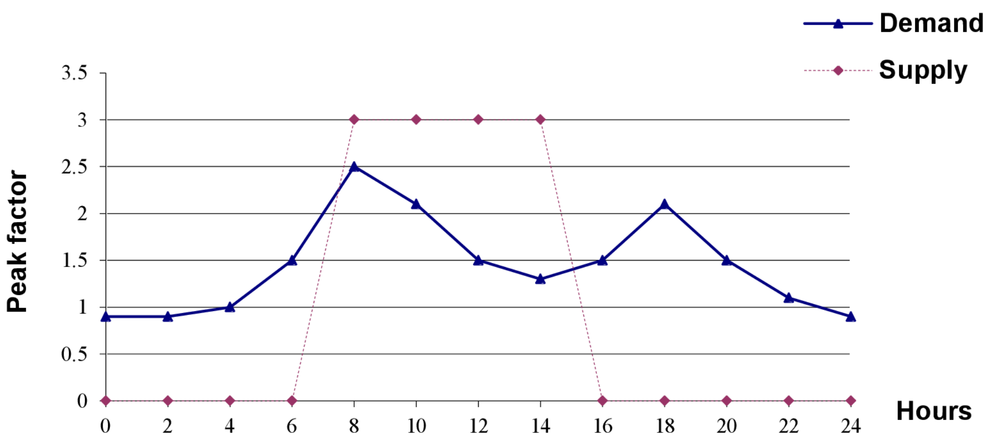


Fig. 2 Daily water demand vs. Daily water supply patterns

Water demand from the network in IWS systems during supply period consists of two amounts of water, one is to meet the consumers demand and the other is to fill the households' tanks, the customers meet water deficit, which is clear in the chart, from private water sources by tanker trucks, Fig.3

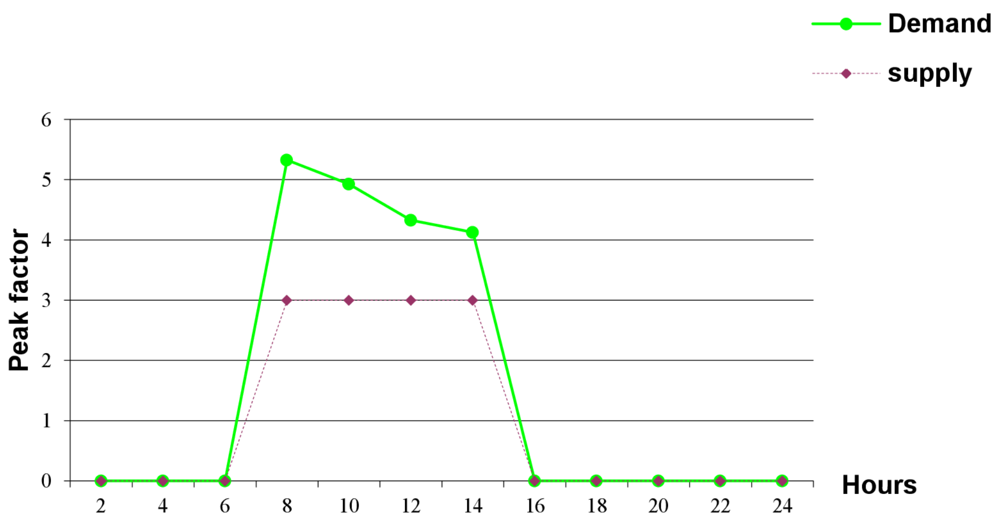


Fig. 3 Water demand from the network during supply period

In IWS systems, consumers consume water from the network Fig.3 during supply period and from the households' tanks Fig.4 during interruption period.

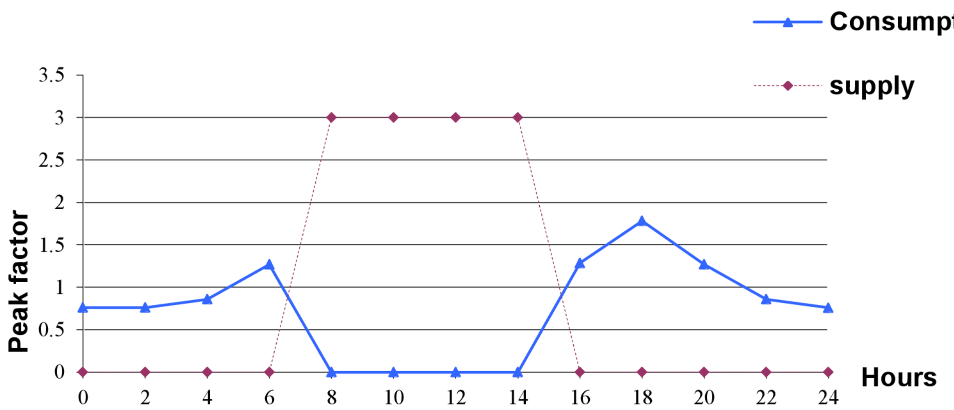


Fig. 4 Daily water consumption from the household tank

So many studies were carried out to describe IWS systems, suggest methods and approach to model this kind of systems, identify and estimate the health risks for humans, study the water quality and the contamination problems, and to compare Intermittent with Continuous water supply systems.

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 (4); 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 (10).

The construction of individual pumps and tanks further reduces the pressure and supply of water available to other consumers and complicating the hydraulics of the system (10).

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 (11).

Generally we can notice that, the peak factors of demand for IWS are higher than peak factors for CWS

Table.1. presents study's results; there are differences in pressure, consumption, supply and average flow (11)

Table 1 Subhash and Prakash study results (11)

Parameters	IWS				CWS			
	Ghaziabad	Jaipur	Nagpur	Panaji	Ghaziabad	Jaipur	Nagpur	Panaji
Duration of supply—*h*	10	3	16	5	24	24	24	24
Per capita consumption—*Lpcd*	175	174	209	120	249	193	232	158
Pressure—*m of water column*	0–25	8.2–19	1.2–10	1–21	1.5–12.5	18–25	1.4–24	2–24
Supply—m^3/d	482.6	197.0	924.6	185.2	770.7	299.5	1093.0	298.1
Average flow—m^3/h	48.3	65.7	57.8	37.0	32.1	12.5	45.5	12.4
Peak factor	6.15	4.38	2.00	6.40	3.06	1.66	2.02	1.98
NRW—*% of total supply based on:*								
a) Average consumption	27.0	19.5	32.0	35.8	34.1	31.0	35.0	47.8
b) Field study	21.0	11.0	28.0	32.6	12.0	62.0	44.0	56.8
Negative for fecal coliform bacteria—%	24	73	37	60	48	91	93	100

CWS—continuous water supply, IWS—intermittent water supply, Lpcd—litres per capita per day, NRW–nonrevenue water

Moreover, continuous water systems are safer than intermittent systems in human health field, in a sample of four different cities; all 48- 100% samples were negative for fecal coliforms during continuous supply versus 24 – 73 % were negative during intermittent supply (11).

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 (12).

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 (13).

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 (14), (15).

IWS systems are unique in it, so many factors make it different from CWS systems such as initial network charging, pressure-dependent water demand, pressure design, application of peak factors, changing resistance coefficients, equitable water distribution using zoning valves, leakages ...etc. so it needs different approach for modeling.

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)

A comparative study of existing town in northern India is presented for the design of new water supply system using present design practices and a proposed design method. The attempt has been made using “EPANET” software and it suggested new method that is more practical and realistic for the design of intermittent drinking water systems (16)

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

2.2 Overview of Risk Analysis Projects and techniques:

A wide variety of different methods exists and many projects were carried out in risk analysis in water supply field.

In the following section, several Water Risk Analysis projects; Hazard Identification methods and Risk Estimation techniques are described:

2.2.1 Water Risk Analysis projects

2.2.1.1 WaterRisk project

WaterRisk project has been carried out by Institute of Municipal Water Management / BUT; Local water supply Utility and National Institute of Public Health in Czech Republic during 2006-2010.

The project developed Risk Analysis methodology and a software tool in the frame of the HACCP methodology (Hazard Analysis at Critical Control Points) to achieve high level of drinking water quality and safety, the developed methodology has been continuously consulted with water utility operators and implemented on some real water-supply systems with continuous supply patterns in Czech Republic (4)

In WaterRisk project, Risk Analysis methodology (RA) is defined as a systematic pre-defined process 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. Hazards that may either affect water quality or interrupt the service and the undesired events that are consequences of the hazards are been specially focused on, Risk Analysis tries to answer the following three principal questions (4)

- What can go wrong? (UE)
- How likely is it? (Probability or frequency analysis)
- What are the consequences? (Consequence analysis)

Risk is defined as a combination of the frequency, or probability, of occurrence and the consequence of an undesired event, that definition is expressed in the Equ.3.

$$R = P.C \tag{3}$$

Where

R is the risk level,

P is the probability of occurrence of the UE,

C is the criticality (the consequence).

According to RA methodology, water supply system should first be described, decomposed into its components according to components catalogue, identified if it is simple or complex system and then to be analyzed.

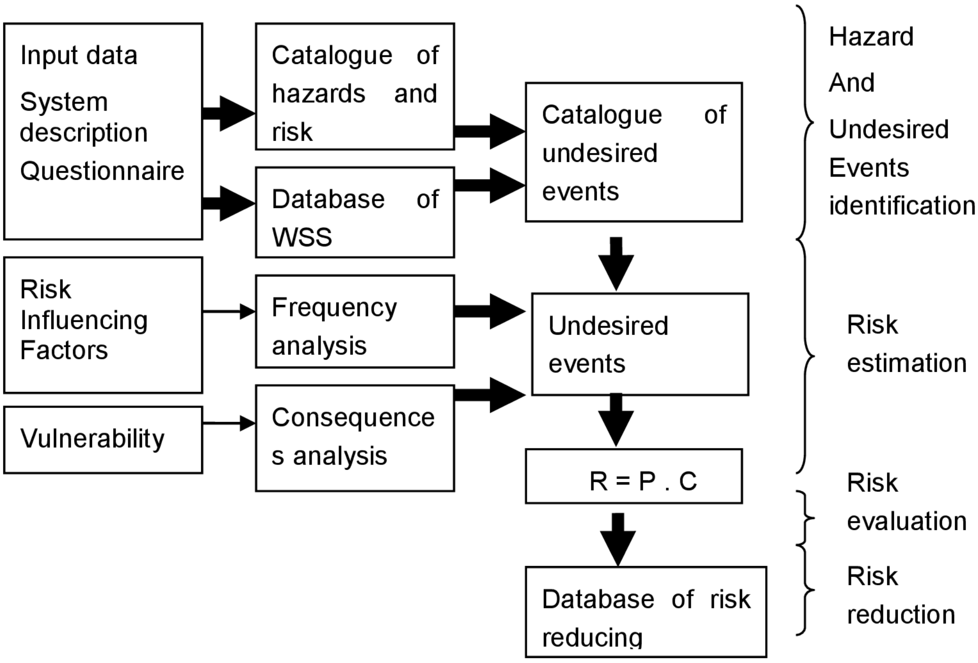


Fig. 5 Generic framework of risk analysis of water supply system- WaterRisk (4)

2.2.1.2 Technology Enable Universal Access to safe water (TECHNEAU) project:

TECHNEAU (2006-2010), an integrated project funded by the European Commission, challenges the ability of traditional system and technology solutions for drinking water supply to cope with present and future global threats and opportunities.

TECHNEAU develops tools and methods applicable for water utilities to relate the risk analysis methods for relevant decisions with respect to risk in the water supply system (5)

Risk Assessment and Risk Management in TECHNEAU project is to integrate risk assessments of the separate parts in drinking water supplies into a comprehensive decision support framework for cost-efficient risk management in safe and sustainable drinking water supply. The framework should be regarded as a structure and toolbox for risk assessment and risk management in Water Safety Plan. It should be applicable to both groundwater and surface water supply systems, with basic as well as more complex designs. The framework should also be applicable on both the operational and strategic levels. (5)

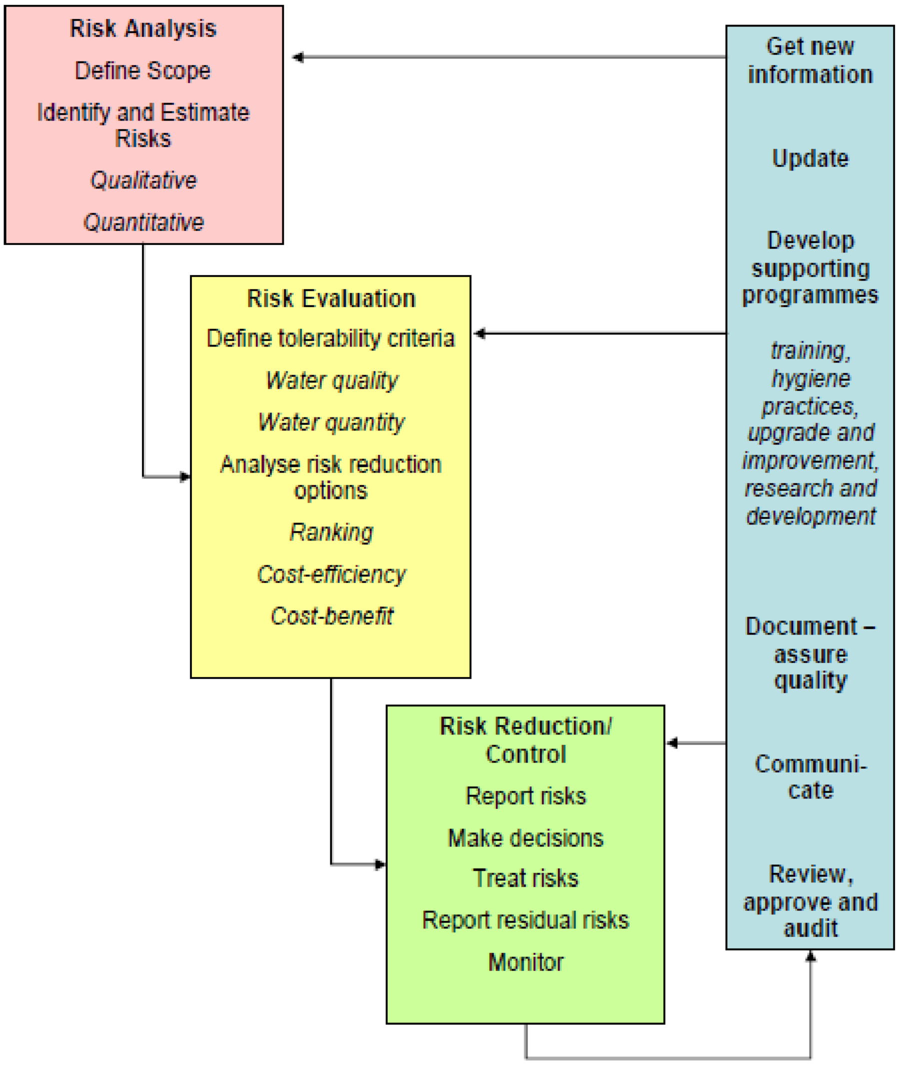


Fig. 6 Generic framework of Risk Management of WSS – TECHNEAU (5)

The framework provides:

- Principles for good risk management practice
- The relevant set of tools necessary for performing the risk assessment and management
- Description of these tools, e.g.: TECHNEAU Hazard database, THDB; Risk analysis methods description; TECHNEAU Risk reduction options database, TRDB and Decision support tool
- Clear examples of risk assessment applications and testing of these tools

2.2.1.3 Failure Experience Improvement System (FEIS)

FEIS is a system founded by the Austrian program for security research 2012, the purpose of it is to build cause-effect chains network for the water supply system, analysis this network in order to support the decision-making by importance-ranking the failures, minimizing that failures, exchange experiences … etc.

There is a high potential to prevent future failures by failure analysis and by sharing failure experiences with others.

FEIS flow diagram:

Sector ⟶ Category ⟶ Part ⟶ Event (failure events).

For every failure there are some causes and effects, each effect considered as a new failure Fig.7.

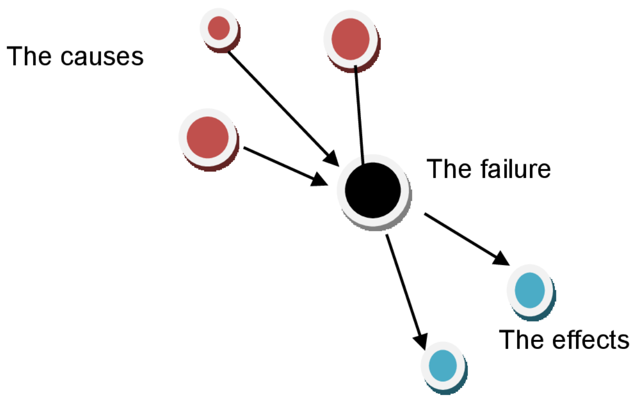


Fig. 7 Cause-effect chain – FEIS (17)

By this way we will have a network of cause-effect chains, in this network we can calculate the vulnerability and determine the critical failure pathway in the water supply infrastructure (17).

2.2.2 Hazard identification techniques

2.2.2.1 HAZard IDentification Analysis (HAZID)

HAZID is a collection of techniques and methods to identify the hazards in the system, such as:

1. What-If analysis:

The team asks questions beginning with "What- if", through this questioning process, an experienced group of personnel identifies possible hazards or accident scenarios.

2. Checklist:

A checklist is easy to use and is a cost-effective way to identify common and customarily recognized hazards (IEC, 1995; USDOE, 2004).

3. Crawford slip:

It is a method to collect ideas from a large group of people, depending on giving out sets of paper slips to everyone in the group and ask them to write one idea per slip about a specific topic.

4. Experience from the past.

2.2.2.2 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. (18); (19)

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

In the beginning, the studies were called operability studies, they were based on the assumption that a problem can only arise when there is a deviation from what is normally expected (20).

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 (21)

Bendixen (22) 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 (18) provided in his publication guidance to HAZOP (Hazard and Operability) and What-If review teams associated with the petroleum, petrochemical and chemical industries.

Schurman and Fleger (23) proposed a novel method for incorporating analysis of hazards introduced by human error into standard HAZOP by adding a new set of guidewords (such as missing, mistimed) and parameters (person, information, action) to focus on management and organizational factors that can contribute to the risk.

Khan and Abbasi (24) have proposed an optimum HAZOP study procedure that uses expert system and proper management of some of the key steps. This procedure is optimal in terms of duration of study, effectiveness and reliability of the results.

Pátkai (25) 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. Thus, safety experts could utilize the tool for HAZOP data-management and not only represent data intuitively, but search for important information from the analysis.

A functional HAZOP assistant is proposed and investigated in a HAZOP study at Technical University of Denmark-Chemical and Biochemical Engineering, functional HAZOP methodology lends itself directly for implementation into a computer aided reasoning tool to perform root cause and consequence analysis (26).

Executing the method relies on using guidewords (such as, no, more, less) combined with process variables - parameters (e.g., Total and fecal coliforms, flow, pressure) that aim to reveal deviations (such as: less pressure than, more PH than) of the process intention or normal operation. This procedure is applied in a particular node as a part of the system characterized for a nominal intention of the operative parameters (27)

The guidewords and process variables should be combined in such a way that they lead to meaningful process variable deviations. Hence, all guide words cannot be applied to all process variables (24).

HAZOP analysis process is executed in three phases as illustrated below (28)

1. Definition Phase

- Preliminary identification of risk assessment team members,
- Identify the assessment scope: The risk assessment team must define study boundaries and key interfaces as well as key assumptions.

2. Preparation Phase

- Identify and locate supporting data and information,
- Identify the end users of the study outputs,
- Prepare project management preparations (ex: schedule of meetings, transcribing proceedings, etc.),

- Prepare template format for recording study outputs,
- Set HAZOP guidewords to be used during the study.

3. Examination Phase (5):

- Split the system into study nodes,
- At each study node specify a relevant set of process variables (parameters), such as temperature, pressure, flow level, and chemical composition.
- Apply guidewords one at a time for all process parameters in order to identify possible deviations and document the study in a worksheet.

The team leader should plan and decide the schedule, duration of review meetings, and arrange the essential documents such as drawing plans, operating procedure; the team leader has to decide the beginning point (scope of the study) and boundaries of study (24).

The team members try to imagine ways in which hazards and operating problems might arise in a network.

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 (24)

2.2.2.3 Preliminary Hazard Analysis (PHA)

PHA is an inductive analysis method where the objective is to identify the hazards, hazardous situations and events that can cause harm for a given activity, facility or system (IEC, 1995).

2.2.2.4 TECHNEAU Hazard Database (THDB)

THDB methodology presents a comprehensive list of hazards and hazardous events that can serve as a checklist for water utilities; it is detailed to help end-users working in water supply system in all steps of development to carry out the hazard identification process, by providing a catalogue with potential hazards of technical, environmental or human origin for the entire system (29).

The database has to be generic for ease of use and at the same time be complete for providing sufficient information (30).

According to THDB, water supply system is subdivided into 12 sub-systems, 10 of them are physical sub-systems representing the installations, one is a non-physical subsystem representing organizational aspects, and one is representing future hazards.

2.2.3 Risk Estimation techniques

2.2.3.1 Failure Modes, Effects, and Criticality Analysis (FMECA)

FMECA is often the first step in a reliability analysis and involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, causes, and effects of such failures (31).

FMECA involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, causes, and effects of such failures, it is usually carried out during the design phase of a system in order to reveal weaknesses and potential failures at an early state.

2.2.3.2 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 (31)

Ericson (32) 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 (32)

In 1965, Boeing and university of Washington sponsored 1st System Safety conference where several papers were presented FTA that make it spread worldwide, then in 1971 the nuclear power industry began using FTA in the design and development of nuclear power plant.

Within the nuclear power industry, the U.S. Nuclear Regulatory Commission began using Probabilistic Risk Assessment (PRA) methods including FTA in 1975, and significantly expanded PRA research following the 1979 incident at Three Mile Island. This eventually led to the 1981 publication of the NRC Fault Tree Handbook NUREG–0492

During 1981-recent, FTA has also been adopted by the chemical process industry, the auto industry, robotic industry and water management field and so many others (32)

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 (6)

A new approach based on a combination of traditional predictive modeling, and event/fault tree analysis techniques, which allow the representation of normal and abnormal (i.e. failures) variations of parameters throughout the food chain and in the processing parameters in the food industry for a better estimation of the real impact of such deviations and failures on consumer safety (33)

A properly constructed fault tree provides a good illustration of the various combinations of (component) technical failures, human errors, normal events, and environmental factors that may result in a critical event for the system (5)

Critical event is called the top event of the FT and the events on the lowest level are called basic events, various events are connected through logic gates, OR gates or AND gates (34)

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 (6)

A fault tree is tailored to its top event which corresponds to some particular system failure mode, and the fault tree thus includes only those faults that contribute to this top event. Moreover, these faults are not exhaustive- they cover only the most credible faults as assessed by analyst (34)

It is important to understand that FTA is not a model of all possible system failures or all causes for a system failure.

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

1. System and boundary conditions definition

Describe studied system; define the boundary conditions, initial state of the system and operating conditions.

2. Top event selection

Define particular failure mode to analyze, the Top event, which should describe WHAT the undesired event is and WHEN it happens.

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.

4. FT Evaluation

Evaluation process is to identify minimal cut sets, compute the probabilities and compute criticality measures.

FTA may be qualitative or quantitative evaluation depending on the objectives of the analysis:

- Qualitative, is to generate the cut sets only, and
- Quantitative, is to generate the cut sets, probabilities, and importance measures, more details in section 3.4.2.6

Minimal cut set is a unique set of events that together cause the UE to occur, it consists one or many events.

Path set is a group of events that if none of them occurs, the top UE event won't occur.

$$P(E) + P(\bar{E}) = 1 \qquad 4$$

Where

$P(E)$ is the probability of Minimal cut set and

$P(\bar{E})$ is the probability of Path set

2.2.3.3 Event Tree Analysis (ETA)

ETA is a forward logic diagram that examines all possible responses to the initiating event progressing left to right across the page (31).

ETA is normally carried out in the following steps as it used in Hong and Lee study (35):

1. Identifying initiating event
2. Selecting safety functions

The safety function (SF) is general countermeasures against certain expected problems; it may be sequenced from specific initiating events.

3. Construction of ET

Construct the ET diagram then the success or failure of the applied SF has been identified on the top of each branch as either ‘Yes’ or ‘No’.

Under risk estimation techniques, we can also mention: Reliability Block diagram; Barriers and Bow-tie diagrams, and Human Reliability Assessment (HRA).

2.2.3.4 Discussion of used methods in risk estimation in the research

Section 2.2 defines the most common projects, methods and techniques in risk analysis field and focuses with details on HAZOP and FTA methods which I used in my research.

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

- 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 (36)

About DS-Evidence theory, Evidence theory was first proposed by Dempster (1967, 1968) and later extended by Shafer (1976). This theory is also called Dempster–Shafer theory (DST) (37)

DST became known to the safety and reliability community in the early 1990s (38)

DST is very useful to express uncertain judgments of experts; its calculus describes the subjective viewpoint as an assessment for an unknown objective fact (36)

When the ignorance or conflicts in the available data are significantly high, a Bayesian approach may not properly aggregate multi-expert knowledge because Bayesian approach is based on probability theory; it aggregates data without differentiating aleatory and epistemic uncertainties. Moreover, it requires prior information which sometimes limits its application to updating existing information, DS-Evidence theory addresses these issues effectively and it is able to combine multi-expert knowledge by taking into account ignorance and conflicts through a belief structure (39)

Cheng (40) paper shows that the lower/upper bound intervals obtained from evidence theory can be used to calculate the failure probability interval of the top event directly, i.e. without needing to transform into 3-valued forms like in Guth approach.

DST as presented in Rakowsky article is based on a scenario that contains the system with:

- Hypotheses (the possible states/ consequences),
- Pieces of evidence (events that occurred or may occur in the system/ causes)
- Data sources (experts, operators or organizations which have to be representative and free of bias)

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”}. (38)

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 Fig.8, it takes into account the ignorance and conflicts in multi-expert knowledge and provides a range for the event probability, and Bet estimate value gives a point estimate in a belief structure (similar to defuzzification in fuzzy set theory) (41)

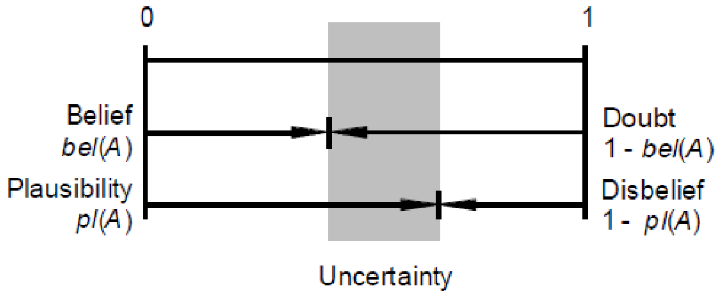


Fig. 8 Measures of belief and plausibility (41)

DS uses basic parameters Equ.5, Equ.6, Equ.7 and Equ.8:

- Basic probability assignment (bpa), which known as belief mass $m(p_i)$ that represents the degree of expert belief for each subset (Note: belief mass is not a probability) (36):

$$m(p_i) \to [0,1]\,; m(\emptyset) = 0\,; \textstyle\sum_{p_i \subseteq p} m(p_i) = 1 \qquad 5$$

- Belief measure (Bel):

$$Bel(p_i) = \textstyle\sum_{p_k \subseteq p_i} m(p_k) \qquad 6$$

- Plausibility measure (Pl):

$$Pl(p_i) = \textstyle\sum_{p_k \cap p_i \neq \emptyset} m(p_k) \qquad 7$$

- Estimate value (Bet):

$$Bet(T) = \textstyle\sum_{P \subseteq p} \frac{m(p_i)}{|p_i|} \qquad 8$$

The knowledge obtained from multiple experts requires aggregation to be used, the combination rules allow aggregating the individual beliefs of multi-experts (e.g. DS and Yager rules) (41).

The most common combination rules include:

Yager, Smets, Inagaki, Dubois and Prade, Zhang, Murphy, and more recently Dezert and Smarandache (39)

Combination rules use orthogonal sum equation, Equ.9:

$$m_{1-n} = m_1 \oplus m_2 \oplus \ldots\ldots.\oplus m_n \qquad 9$$

Where

m_i is the minimal cut set i

$\oplus$ is the operator of combination

For example, according to DS combination $m_1 \oplus m_2(p_i)$ equals:

$$0 \; for \; p_i = \emptyset$$

$$\frac{\sum_{p_a \cap p_b = p_i} m_1(p_a) m_2(p_b)}{1-k} \quad for \; p_i \neq \emptyset \qquad 10$$

According to Yager combination $m_1 \oplus m_2(p_i)$ equals:

$$0 \; for \; p_i = \emptyset \qquad 11$$

$$\sum_{p_a \cap p_b = p_i} m_1(p_a) m_2(p_b) \;\; for \; p_i \neq \Omega$$

$$\sum_{p_a \cap p_b = p_i} m_1(p_a) m_2(p_b) + k \;\; for \; p_i = \Omega$$

Where

k measures the degree of conflict between the two experts

$$k = \sum_{p_a \cap p_b = \emptyset} m_1(p_a) m_2(p_b) \qquad 12$$

- Monte Carlo method

Monte Carlo method (MC) was invented in 1946 by Stanislaw Ulam, a Polish born mathematician, while he was determining the probabilities of winning in a card game of solitaire. MC method 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.

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).

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 (41)

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) (41)

Nicholas Metropolis and Stanislaw Ulam (Izquierdo, 2004) presented motivation and a general description of MC method dealing with a class of problems in mathematical physics. It is, essentially, a statistical approach to study of differential equations, or more generally, of Integra differential equations that occur in various branches of the natural sciences.

3 BASIC STRUCTURE OF THE METHODOLOGY

3.1 Description of studied IWS system

In general, water supply system with intermittent pattern could be:

- Designed, modeled and operated as intermittent water supply, for example Ajman water supply network, or
- Designed and modeled as continuous water supply then operated as intermittent water supply because of changes in circumstances, for example Damascus water supply network.

Intermittent water supply networks have additional elements for each node:

- Storage system for each demand node (building or group of buildings) in the system, or
- Storage system for each customer node (Flat or house) in the system.

The consumers of water are not restricted only by the pressure that is available in the distribution network, but also they are restricted by the capacity of the roof and ground storage tanks.

From the hydraulic point of view, when the consumers are using the water from their storage tanks, they are disconnected from the distribution system, and two independent patterns can be distinguished in this case:

- 1st pattern is at the customers tap which is actually a consumption pattern, Fig.4.

- 2nd pattern is at the tank which is actually a filling pattern, and it is a consequence of the hydraulic operation of the network, representing a pressure related discharge, and it differs for each node in the 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:

- Household (roof or attic) water storage tanks.
- Household water pumping system.

3.1.1 Household water storage tanks

In Damascus suburbs, it is common to use attic tanks or roof tanks Fig.9.

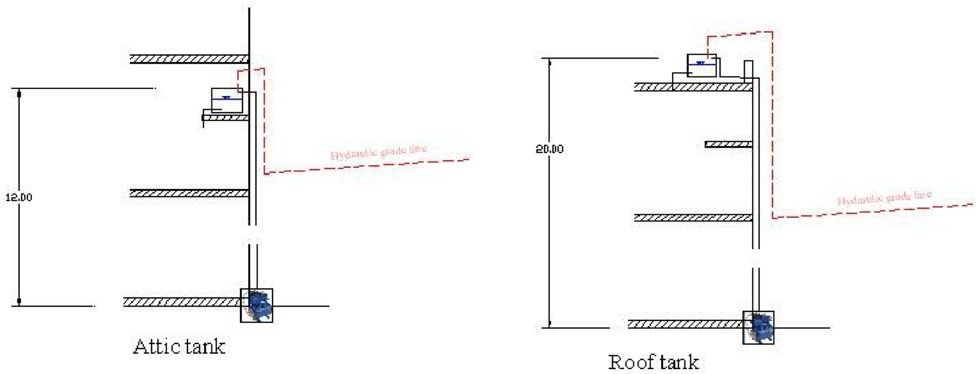


Fig. 9 Attic and roof water storage tanks

The used households' water storage tanks have wide range of sizes, materials and shapes.

According to the materials, households' water tanks could be classified into:

1. Corrugated Galvanized Steel water storage tanks

They could have many shapes, the most commons are round Fig.10 or rectangular; these tanks are internally coated with approved certified coatings to use it for potable water (42).

Although very popular in the past these corrugated galvanized tanks are being outsold by the Plastic (Polyethylene) tanks, Possibly due to the lower cost and the Poly tanks look nicer and can be manufacture in just about any form and colored to fit into the surrounding environment.

Fig. 10 Steel water storage tank (43)

2. Plastic (Polyethylene) water storage tanks

Plastic storage tanks are available in an extremely wide range of sizes and shapes, the most commons are round, slim line Fig.11 (becoming popular due to houses being built on smaller blocks) or rectangular. Research shows that the size of these tanks can vary between 700 and 5,000 liters, water storage tanks also can be purchased in a variety of colors.

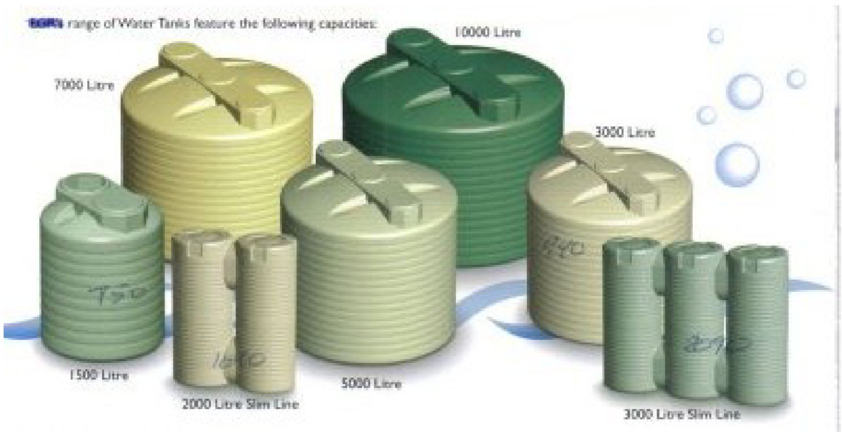


Fig. 11 Polyethylene water storage tanks

An advantage of Plastic Tanks is that they are made from light weight materials. The weight saving means lower costs and greater ease of transport, handling and positioning. Tanks made from plastic are usually less likely to react to the liquid which is stored in them (44).

3. Bladder water storage tanks:

Bladder storage tanks are becoming more popular nowadays due to lack of space in the modern homes, they can be installed under houses, decks or on the attic Fig.12. and could be removed when the owner decides to relocate.

Potable water bladder tanks are made out of material approved for storing consumable liquids and come in sizes up to 10,000 liters (42).

Fig. 12 Bladder water storage tank (45)

According to the capacity, the water storage tanks could be classified into:

1. Small water storage tanks

The capacity is between 100-500 liters

2. Average water storage tanks

The capacity is between 500-2000 liters

3. Big water storage tanks

The capacity is more than 2000 liters

According to the shape and positioning, the water storage tanks could be classified into:

1. Round water storage tanks

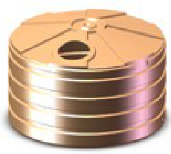


Fig. 13 Round water tank

2. Slim-line water storage tanks

Fig. 14 Slim line water tanks

3. Rectangular water storage tanks

Fig. 15 Rectangular water tank

4. Vertical water storage tanks, Fig.13
5. Horizontal water storage tanks, Fig.15

3.1.2 Level Control valves

The storage tank should be provided with LCV (Level Control Valve) to control the water level and stop overflow water.

1. Float valves

Float valve is a machine for avoiding overflow and backflow while filling water tanks (in the event of low water pressure) . The modern float valve was invented by Joseph Bramah and Thomas Twyford (8).

Fig. 16 Float Valves (46)

It is designed to either full open when water level reaches a predetermined low point or full closed when a predetermined high point is reached.

It is a hydraulically operated with pilot controlled valve which is actuated by a float ball to limit the high and low liquid levels in the tank or reservoir by closing or opening the main valve. High and low liquid levels are adjustable.

The installation of float valve is clearly described in the Fig.17

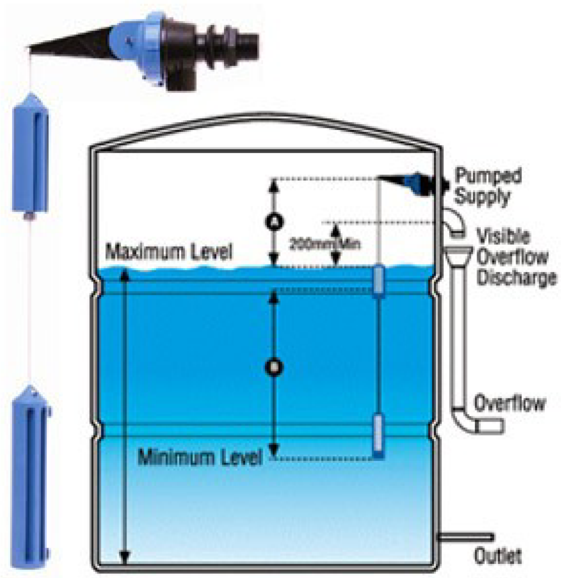


Fig. 17 Installation of float valve in the tank (46)

2. Modulating float valves

They can be installed to proportional control the flow into or out of the tank by either partially closing on or partially opening on. It is a hydraulically operated and pilot controlled valve, Fig.18

Fig. 18 Modulating float Valve (46)

3. Altitude valves

The main valve is controlled by a highly sensitive pilot, it is located outside the tank. The pilot opens or closes the valve in response to the static pressure of the water, closes at a preset maximum water level to prevent overflow of a storage tank and opens to refill when the water level in the tank lowers, the pilot allows for differential adjustments between the maximum and minimum level (46).

Altitude Control Valve is accurate, automatic level control, without the use of floats or sensors, it could be one-way flow is used for tank fill only or two-way flow into and out of the tank.

Fig. 19 Altitude Valve (46)

It is installed out of tank as shown in the Fig.20

Fig. 20 Altitude valve position (48)

4. Water level sensor

The water level sensor is conducive for liquids that have a conductivity of equal to or more than 25m Siemens. It is a good choice for a water level switch.

3.1.3 Household water pumping system

In general, the used pump's type for domestic purpose is horizontal centrifugal pump.

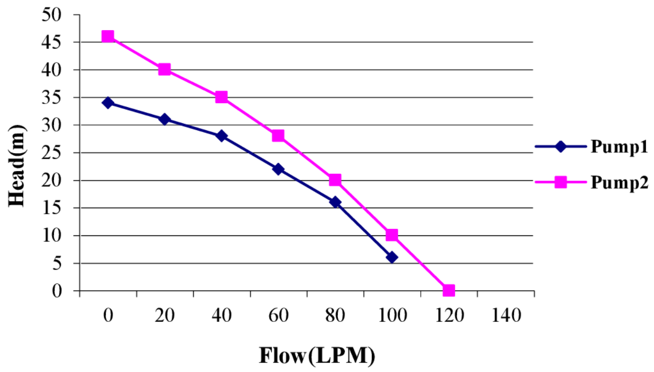


Fig. 21 Example of household water pump Q-H curves

Household water pumps are selected based on the following criteria:

- Required flow, high performance, for single flat 20-100 LPM Fig.21
- Required head (lift), high performance, for single flat 15-50 m Fig.21
- Space constraints, the size
- Whether it is likely ever to be run dry,
- Whether it needs to be self-priming
- Hydraulic and motor efficiencies - less energy consumed,
- Pump and motor design – reliability improvements,
- The customized options – e.g. alternative seals and voltage ranges,
- Drink water compatible,
- Quieter in operation, and the price

3.2 Risk Analysis Methodology for IWS systems

For intermittent water supply system, Fig.22 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.23

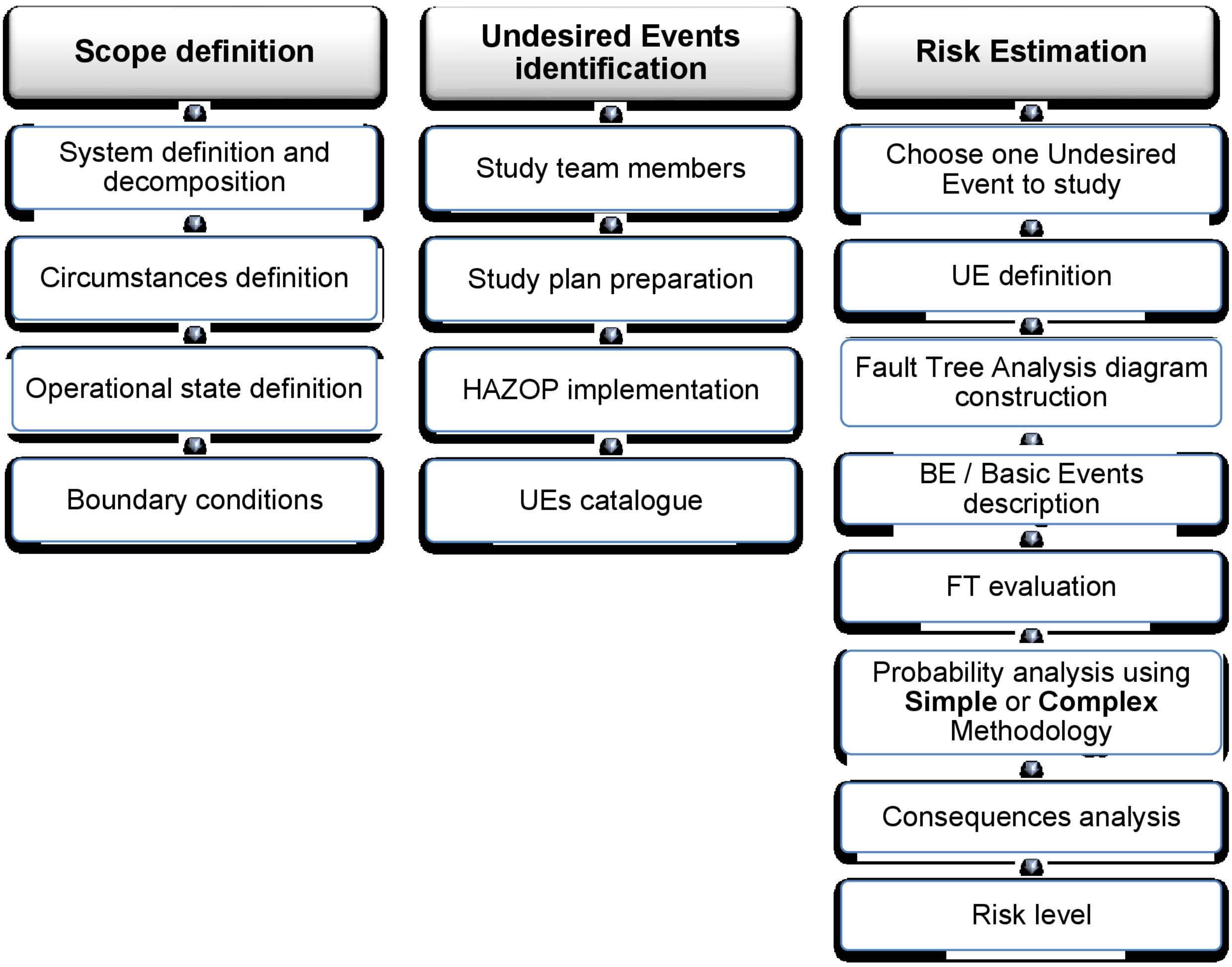


Fig. 22 Generic framework of Risk Analysis Methodology for IWS systems

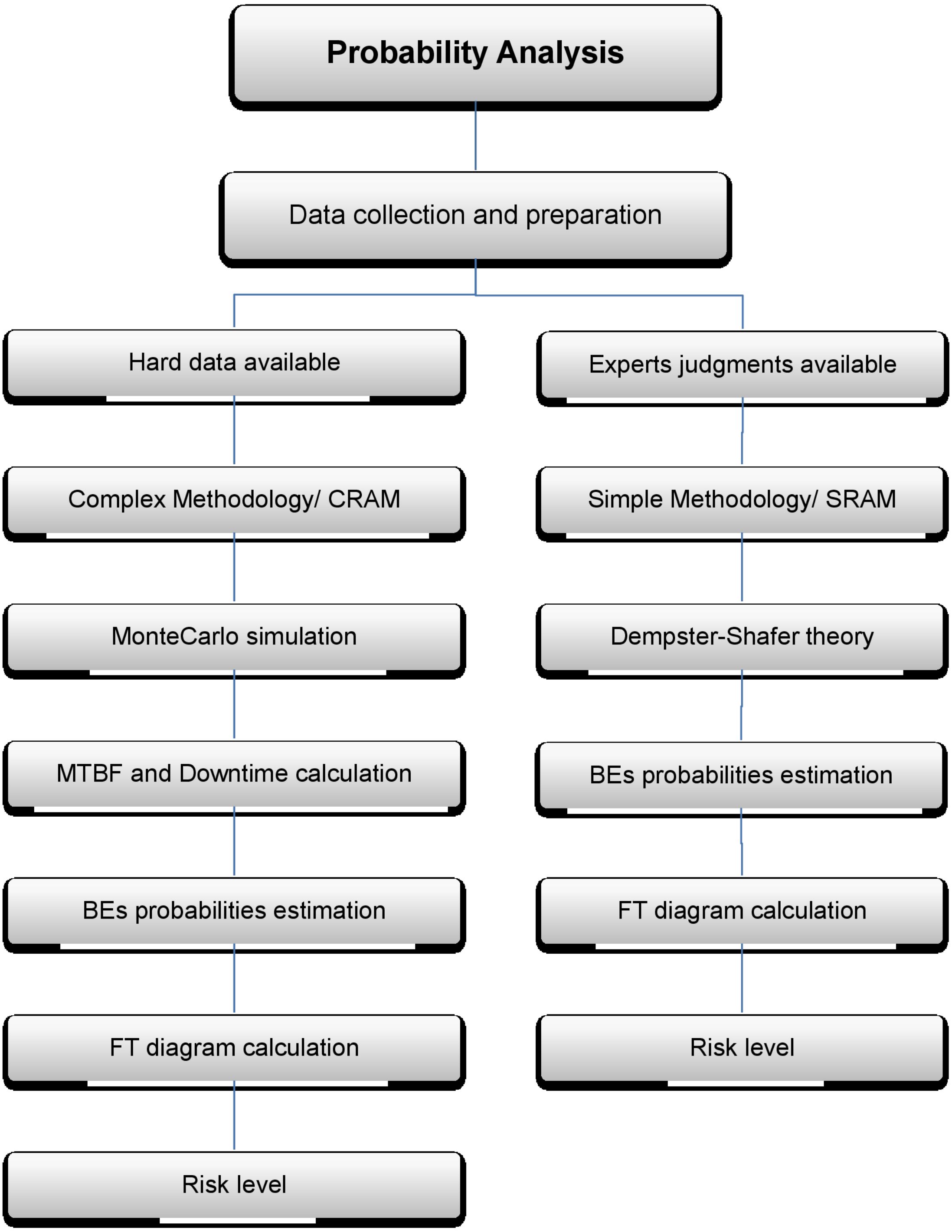


Fig. 23 Probability Analysis under Simple and Complex Methodology

3.2.1 Hard data

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.
- Any pre-existing compiled data taken from previous studies on the system.
- Buildings documentation: current and future projects.
- Documentation of technical executed reconstruction: water supply network, objects.
- Highest and lowest temperatures, climate in the region.
- Old used technologies.
- Analysis of the distributed water in the last 5 years, if it is available.
- Analysis of inflow and outflow and changes in water storage levels in the reservoir.
- Survey pipelines
- Technical information about valves: valves types, casting year, replacement records, locations, technical state and maintenance frequency.
- Technical condition of the drainage and characters of the sewer system network.
- Knowledge about paralleling and crossing areas with sewer system and heat water system.
- Records of pumping station, the technical condition of the pumps and information about previous failures and repairs.
- Information about the end-users (consumers)

3.2.2 Complex Risk Analysis Methodology

CRAM steps as shown in Fig.22:

- Scope definition,
- Undesired Events Identification,
- Risk Estimation:
  - Fault Tree diagram construction,
  - Probability analysis with **available data** Fig.23 , briefly the major steps:

    1. Estimate the probability P_i for each basic event BE_i under uncertainty by modelling the available data and performing the calculations with Monte Carlo simulation since hard data is available, more detail in section 3.4.3.1

    2. Calculate the probability of occurrence of top event using Fault Tree equations, Equ.31

  - Consequences analysis (the number of consumers affected), more detail are available in section.3.4.4
  - Risk level evaluation Equ.41, Equ.42

3.2.3 Simple Risk Analysis Methodology

SRAM steps as shown in Fig.22:

- Scope definition,
- Undesired Events Identification,
- Risk Estimation:
  - Fault Tree diagram construction,
  - Probability analysis with **No available hard data** Fig.23, briefly the major steps are:
    1. Estimate the probability P_i for each basic event BE_i under uncertainty by applying Dempster-Shafer theory depending on experts' judgments since the hard data is not available, more details in section 3.4.3.2
    2. Calculate the probability of occurrence of top event using Fault Tree equations, Equ.31
  - Consequences analysis (the number of consumers affected), more details are available in section.3.4.4
  - Risk level evaluation Equ.41 and 42

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.

DPSIR framework is useful to clearly managing and analyzing IWS system to identify undesired events and suggest Risk Reduction Strategy.

DPSIR analytical framework is a chain of causal links, table.2:

- **D**riving force: is the need;
- **P**ressure: is the activities that triggers the possible risk and fault into the system;
- **S**tate: is the real and existing state of the system;
- **I**mpacts: are the bad or **Undesired Events** that may happen in the system because of the State
- **R**esponses: are the measures and **risk reduction options** by changing and affecting in Pressure, State, Impacts factors (49)

Describing the causal chain from driving forces to impacts and responses is a complex task, and tends to be broken down into sub-tasks, e.g. by considering the pressure-state relationship.

Table 2 Water risk project for IWS system presented in DPSIR framework

Target	DPSIR Framework	Definition	Risk assessment indicators
Assessing and analyzing risk in IWS system to help decision makers and water companies to develop risk reduction strategy and options.	Driving forces	Water demand	Households, public sectors, tourism, recreation and industry water demand
	Pressures	Existing and expected hazards that causes the possible risk in the system	Depletion in surface and/ or groundwater sources Pollution in raw water and insufficient water treatment plant (unacceptable water quality force water utility to stop delivery) Increasing in domestic, industrial and agricultural water demand Rapid urbanization Financial pressures Other infrastructures failures that are related to the supply system such as electrical power supply Treatment plant, pumping system, reservoir or distribution system failure and no clear and speed programs to maintenance or repair Political pressures and restrictions in case of intercountry water sources
	State	Intermittent water supply strategy	No enough available potable water to supply and no financial or technical ability to treat or find alternative water sources Operate drinking water supply system on Intermittent supply pattern as a rationing strategy .
	Impacts	The undesired events that may happen in the system: quality, operational ,technical and technological impacts on the system & financial and social impacts on the customers Section 3.3.3	Low operational pressure Interruption in water supply, Inadequate hydraulic capacity of the network, Ingress of contaminated ground water or sewage water into the network, Deterioration of microbiological parameters of the distributed water, Deterioration of microbiological parameters of water in storage tanks and cisterns, Biofilm detachment event, Troubles in fire-fighting systems, Biofilm production, High doses of disinfectants, THMs and other disinfection's by-products Production, Unacceptable turbidity values of the distributed water, Deterioration in taste, smell, or temperature of the distributed water, Corrosion the inner surface of the pipelines, Increasing in water losses, Increasing in water consumptions, Equipment, meters, and valves failure Breaks and cracks in the pipelines Financial pressure on the customers (pay for pumps, tanks, households chlorination, water from private source such as tank trucks or water bottles) Health risk for customers.

Target	DPSIR Framework	Definition	Risk assessment indicators
Assessing and analyzing risk in IWS system to help decision makers and water companies to develop risk reduction strategy and options.	Responses	Risk Reduction Strategy: Measures and risk reduction options by changing and affecting in Pressure-State-Impacts factors. Hard measures (control and mitigation) and soft measures (regulations & policies)	Budget allocation for treatment plants maintenance and repair programs. Budget allocation for pumping system maintenance and repair programs. Budget allocation for water resources management projects to find additional resources: Surface water, underground water or to treat or desalinate available water Increase treatment plants capacity and Control treatment process Monitor and control disinfectants doses Household chlorination programs that must be supported by health and water quality and disinfection experts Water resources allocation Emergency response plan to any failure in existing pumping system, reservoir, treatment plants, and distribution system Redundancy pumping system Reduce and control water losses by applying efficient strategies to detect leaks and take speed and efficient reactions as speed repairs or replacement of damage part and control illegal penetrate to the system Control households tanks and pumps: Monitor storage tanks' volumes and pumps characteristics Increase the duration of supply to decrease the withdraw rate, increase the hydraulic capacity of the network and to affect consumers behaviors Redundancy electrical power supply: Find alternative electrical power sources Regular maintenance and flushing program: Clear and regular inspection, maintenance, repair, cleaning and flushing plans should be set to the equipment and pipelines. Increase water tariffs Optimizing operation program Public awareness programs

3.3.1 Hazard Operability Analysis technique (HAZOP) implementation

HAZOP process involves a detailed study of each part of the entire water supply network from transmission main to household connection with the help of supply plan drawings of the network that covering pipes, households pumps, vessels, conduits, connections, valves, and other equipment, the drawings are studied in relation to the operation plan of the network.

HAZOP focuses on the causes that may lead to variations in the designed operational manner due to human errors, process, or material failures, and the likely consequences of those variations.

HAZOP takes into consideration quality and quantity parameters such as flow rate; pressure; PH; total and fecal coli forms.

During examination phase of HAZOP study, team members try to imagine ways in which hazards and operational problems might arise in a network. To cover all possible failures in the network, the imagination of the HAZOP study team members is guided in a systematic way using a set of ‘guide words’ to generate the process variable’s deviations.

HAZOP analysis process is executed in four phases as illustrated below (28):

- Definition Phase

1. Select study team members: team leader; process engineer; operator; safety representative; control system engineer; and maintenance engineer
2. Study team identifies the assessment scope: Defining study boundaries and key assumptions.

- Preparation Phase

1. Identify and locate supporting data and information
2. Prepare project management preparations (example: scheduling meetings, transcribing proceedings)
3. Prepare template format for recording study outputs (HAZOP worksheets)
4. Set HAZOP guide words to be used during the study,
5. The used guide words are showen in table 3:

Table 3 Guide words

Guide words	Meaning	Applicable to following parameters
No/ None	No part of the intended result is achieved	Flow rate – Households pumps characteristics
More than	Quantitative increase	Doses of disinfectants
Less than	Quantitative decrease	Pressure – flow rate
Other than	Something completely different happens	Duration and frequency of supply

- Examination Phase

1. Split the system into study nodes, study nodes in the project could be:

- Node on transmission main
- Node on household's connection
- Hydraulic critical node in the network
- Quality critical node in the network

2. Choose for each study node its relevant parameters or indicators to start brainstorming discussion, as shown in Fig.24 and table.4

Table 4   Study nodes and parameters

System	Study nodes	Parameters/ Indicators
Intermittent Water Supply system	Node on transmission main	Pressure Flow rate Duration and frequency of supply Disinfectant doses
	Node on household's connection	Pump's characteristics Volume of stored water Microbial and chemical indicators in the tank such as: Total and Fecal coliforms; PH; Total and dissolve organic carbon (TOC/DOC)
	Hydraulic critical node	Pressure Water losses in the network till this node (indicator)
	Quality critical node	Disinfectant residual Microbial indicators such as: Total and Fecal coliforms Chemical indicators such as: PH; TOC/DOC

3. Apply guidewords one at a time for all process parameters and document the study in a worksheet.

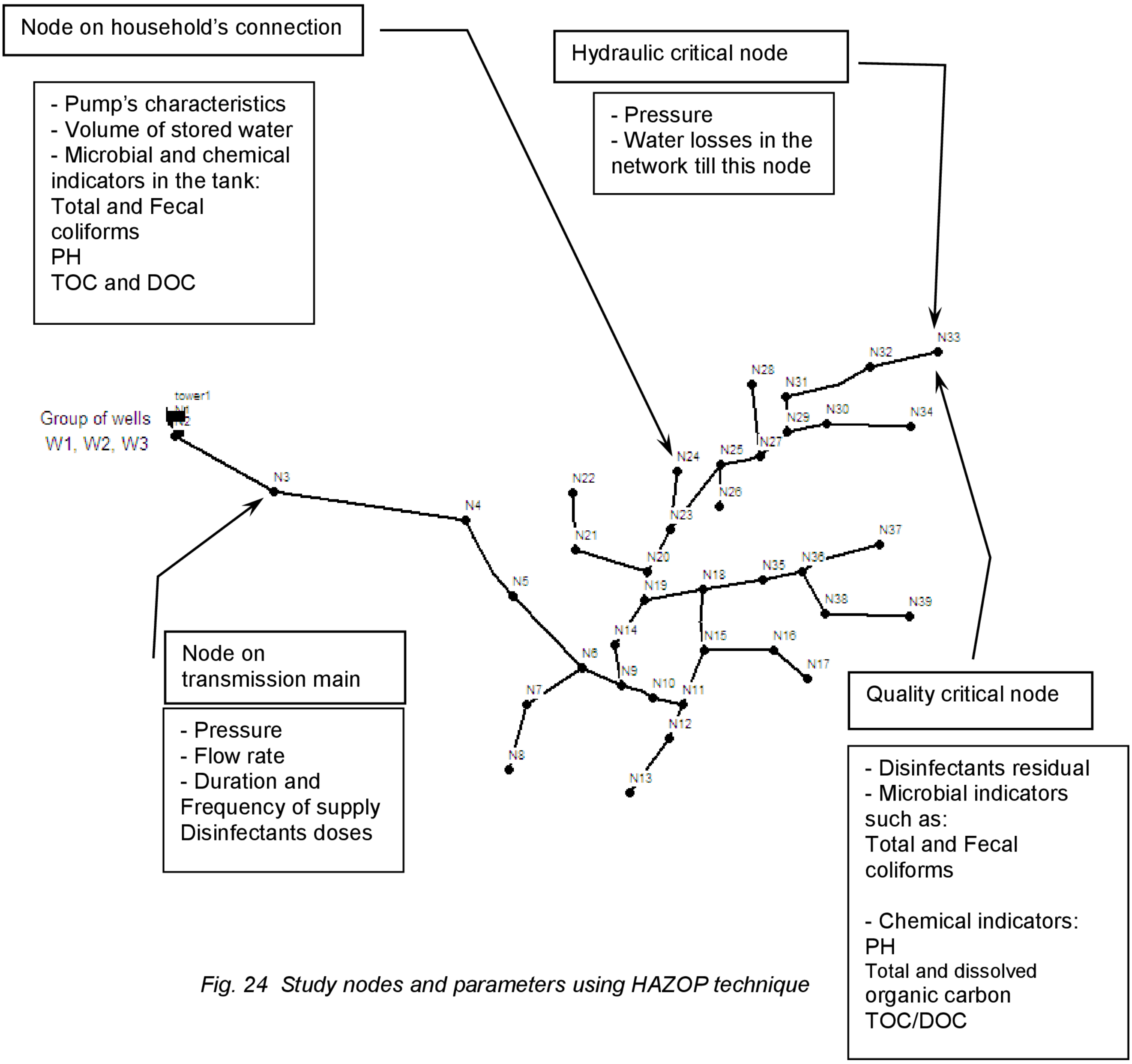


Fig. 24 Study nodes and parameters using HAZOP technique

3.3.2 HAZOP documents

All following HAZOP documents (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.

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.

Even if we relied on the same study nodes and tables, the causes, undesired events or the responses may be changed according to the real situation in studied system.

Table 5 Flow rate parameter in transmission main

Node : water network (Transmission main)				
Parameter: Flow rate				
Guide words	**Deviation**	**Causes**	**Consequences/ Undesired events**	**Responses**
No	Q = 0	No available drinking water sources to feed the system Failure in pumping system Failure in electrical power supply system Failure in treatment plants Failure in reservoir Interruption period according to rationing strategy	Interruption in water supply Ingress contamination into the system Zero pressure Deterioration in microbiological and chemical parameters in the network Stagnant water in the system cause Biofilm production Stagnant water cause deterioration in taste, smell, or temperature Stagnant water cause unacceptable turbidity values Troubles in firefighting system Corrosion in the inner surface of the pipelines and equipment High required doses of disinfectants THMs and other disinfection's byproducts production External load on unpressurized pipes will cause cracks in the pipes and that increase the leakage rate and pipelines failures	Water resources management and allocation projects Budget allocation for pumping system maintenance and repair plans. Emergency response plan to any failure in pumping system or in treatment plant Redundancy of power supply Budget allocation for treatment plants maintenance and repair. Increase treatment plant capacity Budget allocation for rehabilitation and maintenance plans for reservoir.
Less	Q < required	Insufficient water source with no alternative sources available Available water is unacceptable health-based water quality standards and inadequate capacity of treatment plant Part failure in treatment plants Part failure in pumping system Part failure in electrical power supply system Part failure in reservoir Part failure in distribution system High rate of water losses	Low operational pressure Interruption in supply Inadequate hydraulic capacity of the network Ingress contamination into the network Troubles in firefighting system	Water resources management and allocation projects Budget allocation for pumping system maintenance and repair plans. Emergency response plan to any failure in pumping system or in treatment plant Redundancy of power supply Budget allocation for treatment plants maintenance and repair. Increase treatment plant capacity Budget allocation for rehabilitation and maintenance plans for reservoir.

Node : water network (Transmission main)				
Parameter: Flow rate				
Guide words	**Deviation**	**Causes**	**Consequences/ Undesired events**	**Responses**
No	Q = 0	No available drinking water sources to feed the system Failure in pumping system Failure in electrical power supply system Failure in treatment plants Failure in reservoir Interruption period according to rationing strategy	Interruption in water supply Ingress contamination into the system Zero pressure Deterioration in microbiological and chemical parameters in the network Stagnant water in the system cause Biofilm production Stagnant water cause deterioration in taste, smell, or temperature Stagnant water cause unacceptable turbidity values Troubles in firefighting system Corrosion in the inner surface of the pipelines and equipment High required doses of disinfectants THMs and other disinfection's byproducts production External load on unpressurized pipes will cause cracks in the pipes and that increase the leakage rate and pipelines failures	Water resources management and allocation projects Budget allocation for pumping system maintenance and repair plans. Emergency response plan to any failure in pumping system or in treatment plant Redundancy of power supply Budget allocation for treatment plants maintenance and repair. Increase treatment plant capacity Budget allocation for rehabilitation and maintenance plans for reservoir.
Less	Q < required	Insufficient water source with no alternative sources available Available water is unacceptable health-based water quality standards and inadequate capacity of treatment plant Part failure in treatment plants Part failure in pumping system Part failure in electrical power supply system Part failure in reservoir Part failure in distribution system High rate of water losses	Low operational pressure Interruption in supply Inadequate hydraulic capacity of the network Ingress contamination into the network Troubles in firefighting system	Water resources management and allocation projects Budget allocation for pumping system maintenance and repair plans. Emergency response plan to any failure in pumping system or in treatment plant Redundancy of power supply Budget allocation for treatment plants maintenance and repair. Increase treatment plant capacity Budget allocation for rehabilitation and maintenance plans for reservoir.

Table 6 Pressure parameter in transmission main

Node : water network (Transmission main)				
Parameter: Pressure				
Guide words	**Deviation**	**Causes**	**Consequences/ Undesired events**	**Responses**
No	P = 0	Failure in reservoir Failure in pumping system Failure in electrical power supply system Electrical interruption period according to rationing strategy.	Interruption in water supply Ingress of contaminated ground water into the network Deterioration of chemical or microbiological parameters of the water Troubles in fire-fighting systems Stagnant water in the system cause Biofilm production Stagnant water cause deterioration in taste, smell, or temperature Stagnant water cause unacceptable turbidity values External load on unpressurized pipes will cause cracks in the pipes and that increase the leakage rate and pipelines failure.	Redundancy of power supply Budget allocation for pumping system and reservoir manitenance and repair plans. Emargency response plan to any failure in pumping system Emargency response plan to any failure in electrical power system
Less	P < required	Part failure in reservoir Part failure in pumping system Part failure in electrical power supply system Inappropriate operation program	Low operational pressure Interruption in water supply Inadequate hydraulic capacity Troubles in firefighting systems Ingress of contaminated ground water into the network Biofilm detachment event	Budget allocation for pumping stations manitenance and repair plans. Redundancy of power supply Emargency response plan to any failure in pumping system Emargency response plan to any failure in electrical power system Optimizing operation program

Table 7 Duration and frequency of supply parameter in Transmission main

Node : water network (Transmission main)				
Parameter: Duration and frequency of supply				
Guide words	**Deviation**	**Causes**	**Consequences/ Undesired events**	**Responses**
More	12 ≤ t ≤ 24 Daily	Treatment plant failure or insufficient capacity Interruption period according to rationing strategy Failure in pumping system Failure in electrical power supply system	Inadequate hydraulic capacity of the network Troubles in firefighting system Ingress of contamination into the system Biofilm production due to stagnant water and microbial regrowth Deterioration in taste, smell of the water Deterioration of water quality parameters in the distribution system High required doses of disinfectants because the disinfectant residual in water will decrease THMs and other disinfections byproducts production Corrosion the inner surface of the pipelines Corrosion in inner surface of the valves and other equipment Increasing in water consumption due to store water more than required, consumers behaviors	Budget allocation for treatment plants maintenance and repair. Increase treatment plant capacity Budget allocation for pumping system maintenance and repair plans. Redundancy of power supply
Less	4 ≤ t ≤ 12 Not daily	Insufficient water sources Treatment plant failure or insufficient capacity Interruption period according to rationing strategy Failure in pumping system Failure in electrical power supply system	Low operational pressure Interruption in water supply Inadequate hydraulic capacity of the network Ingress of contaminations into the system Troubles in firefighting system Biofilm production due to stagnant water and microbial regrowth Deterioration in taste, smell of the water Microbial growth in the distribution network and water storage tanks, Stagnant water in distribution system will be the first flush to flow into the consumers tanks and cause deterioration of water quality parameters in the tanks Corrosion in the inner surface of the pipelines and other equipment Customers pay for water from private sources	Budget allocation for treatment plants maintenance and repair. Increase treatment plant capacity Budget allocation for pumping system maintenance and repair plans. Water resources management and allocation projects Redundancy of power supply Optimizing operation program

Notes for table.7:

The duration of supply stands to the number of supply hours per day and the frequency of supply stands to the number of supply days per week

The duration and the frequency of supply affect the operational mode of the system, the consumers' behaviors, the required amount of stored water and the quality of water in the storage tanks and the network

The table differs from the standard one; the scenarios consider that 12 hours is the basis of our comparative:

$12 \leq t \leq 24$ refers to more than 12 hours

$4 \leq t \leq 12$ refers to less than 12 hours

The consequences of the both status is the same in definitions, but they differ in the severity (intensity) of the event

For the frequency, we will discuss daily or not daily situations

We will here assume only the boundary cases (marginal cases); I mean the best case and the worst case that we may face in intermittent water supply systems

Table 8 Doses of disinfectant parameter in Transmission main

Node : water network (Transmission main)				
Parameter: Doses of disinfectant (residual of disinfectant measure the amount of contamination in the water) it is a chemical indicator				
Guide words	**Deviation**	**Causes**	**Consequences/ Undesired events**	**Responses**
More	D > MRDL (Maximum Residual Disinfectant Level [11])	Need for high doses due to decreasing in disinfectant residual in response to high contamination of supplied water	THMs and other disinfectants byproducts production	Proper and regular monitoring and controlling of the doses
		High doses of disinfectant due to inappropriate doses schedule	Deterioration in taste and/or odor of the water	Control of treatment processes to reduce disinfectant demand
		Need for high doses due to long-term water stagnant in the network.	Heath risk for the customers	Control of disinfection process to reduce disinfectant doses levels
		Over-dosing may be due to failure in disinfection system		Consideration should be given to re-chlorination during distribution so we decrease the doses in transmission main.
		High-level dosing to ensure adequate concentrations in remote parts of the distribution network		
Less	D < MRDL	Low doses of disinfectant due to inappropriate doses schedule	Deterioration in microbiological parameters of the water	Proper and regular monitoring and controlling of the doses
		Technological failure in chlorination points	Biofilm production	Household chlorination process (solutions or tablets in the home) that must be supported by health and hygiene education and risk reduction
		Low-dosing due to failure disinfection system	Unacceptable turbidity values of water	Control of disinfection process to reduce disinfectant doses levels
			Deterioration in taste or odor of the water	
			Heath risk for the customers	
			Customers must pay for household chlorination process	

Note for table.8:

For table 6, Chlorine is added to water as either in aqueous solution (calcium hypochlorite or sodium hypochlorite) or chlorine gas. Smaller supplies may use tablets of hypochlorite.

Table 9 Pump's characteristics parameter in household's connection

Node : water network (Household's connection)				
Parameter: Pump's characteristics				
Guide words	**Deviation**	**Causes**	**Consequences/ Undesired events**	**Responses**
No or less	No pump Or Q < min. required (l/m) and H < min. Required (m)	Failure in electrical power supply Failure in household pump system Manual household pumping system, and no body knows the water is supplied Using low performance pumps because of low price or size constraints Customers choose pumps without hydraulic background or without experts consulting	Low or zero pressure in this connection Interruption in water supply Customers must pay for water from private sources (such as tanker trucks)	Redundancy of power supply Proper and regular maintenance and repair plans for household pumping system Public awareness and consultancy programs
More	Q > max. acceptable(l/m) and H > max. acceptable (m)	Customers choose pumps without hydraulic background or without experts consulting Using high performance pumps to have more water than others (as somebody think)	High withdraw from the network Low pressure in the network Interruption in water supply in other households' connection (consumers who don't have pumps or have with low performance) Inadequate hydraulic capacity of the network Ingress contamination into the system Biofilm detachment event Corrosion the inner surface of the pipelines Troubles in firefighting system Increasing in the consumption	Public awareness programs Proper and regular monitoring and controlling program of customers pumps

Table 10 Volume of stored water parameter in household's connection

Node : water network (Household's connection)				
Parameter : Volume of stored water				
Guide words	**Deviation**	**Causes**	**Consequences / Undesired events**	**Responses**
No/ less	No storage tank /or Total storage volume < 80% demand	Failure in households water tank Failure in households pumping system	Interruption in household water supply Customers must pay for private water source (such as trucks tanks)	Proper and regular maintenance and repair plans for household pumping system Proper and regular maintenance and repair plans for water storage tanks Public awareness programs
More	Total storage Volume > 120% of demand	Low frequency of supply water per week Consumers inappropriate behavior Low water tariff Peak seasons (Summer) Available large storage tanks Available high pump characteristics	Increasing in water consumption Deterioration of microbiological parameters in the tank	Public awareness programs Regular monitoring and controling program on the household storage tanks Increase the drinking water tariff

Table 11 Total and fecal coliforms parameter in household's connection

Node : water network (Household's connection) Microbial indicators in water tank				
Parameter: Total and Fecal coliforms (measure presence of fecal contamination) microbial indicator				
Guide words	**Deviation**	**Causes**	**Consequences / Undesired events**	**Responses**
More	TC and FC > acceptable value	Fecal contamination due to Opening or failure in storage tanks, breaks in the connection or during repairs.	Deterioration of quality parameters of water in storage tanks	Proper and regular maintenance and repair program for the system
		Bacterial pathogens	Biofilm production in the tanks	Proper and regular flushing and cleaning for the network
		Presence and growth of Biofilm	Need for household chlorination process (customers must pay for this)	Household chlorination process
		Inadequate or loss disinfectant residual	Health risk for the customers	Proper and regular flushing and cleaning for the tank
		Stagnant water in the storage tanks		
		Accumulation of sediments		
		Stagnant water in distribution system		

Note for table.11:

The figure 25 shows bacterial count of the influent water and water after being stored for different periods in house-hold storage tanks. This increase was accompanied by a decrease in turbidity and chlorine residual and an increase in TOC and pH (50)

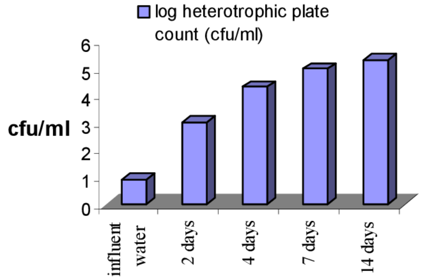


Fig. 25 Bacterial count in stored water in house-hold storage tanks

Table 12 TOC/DOC parameter in household's connection

Node : water network (Household's connection) Chemical indicators in water tank				
Parameter: TOC/DOC Total and dissolved organic carbon / chemical indicator				
Guide words	**Deviation**	**Causes**	**Consequences / Undesired events**	**Responses**
More	TOC/DOC > acceptable level (0.02-0.2) mg/L	Contamination in supplied water	Deterioration of microbiological parameters (Coliform growth) of stored water	Proper and regular maintenance and repair program for the system
		Contamination because breaks and cracks in the connections and tanks	Biofilm production in the tanks	Proper and regular maintenance and repair plan for the households connections and tanks
		Contamination during repairs and installs new tanks and equipment.	Deterioration in taste and odor of the water	Proper and regular flushing and cleaning for the network
		Failure in storage tanks	Health risk for customers	Household chlorination process
		Intrusion		Proper and regular flushing and cleaning for the household tank
		Existence of Biofilm in the tanks		Control of disinfection treatment processes
		Corrosion of the inner surface of the pipelines and other equipment		

Table 13 Pressure parameter in hydraulic critical node

Node : water network (Hydraulic critical node)				
Parameter : Pressure				
Guide words	**Deviation**	**Causes**	**Consequences/ Undesired events**	**Responses**
No	P = 0	Low supplied pressure in the transmission main Interruption period according to rationing strategy. Failure in distribution system High rate of water losses	Interruption in water supply Ingress of contaminated ground water into the network Deterioration of microbiological parameters of the water Troubles in fire-fighting systems Biofilm production Deterioration in water taste, smell, or temperature Unacceptable turbidity values Customers pay for individual households pumps External load on unpressurized pipes will cause cracks in the pipes and that increase the leakage rate	Monitor and increase operational pressure in transmission main Proper and regular maintenance and repair plans for distribution system. Reduce and control water losses by applying efficient strategies to detect leaks and take speed and efficient reactions.
Less	P < required	Low supplied pressure in transmission main Failure in distribution system High withdraw rate High water losses	Low operational pressure Interruption in supply Inadequate hydraulic capacity Troubles in firefighting systems Ingress of contaminated ground water into the network Customers pay for individual households pumps	Monitor and increase operational pressure in transmission main Proper and regular maintenance and repair plans for distribution system Reduce and control water losses by applying efficient strategies to detect leaks and take speed and efficient reactions.

Table 14 Water losses parameter in hydraulic critical node

Node : water network (Hydraulic critical node)				
Parameter: Water losses				
Guide words	Deviation	Causes	Consequences / Undesired events	Responses
More	L > 40%	Poor material and old age of pipelines	High water losses	Regular and proper leak detection and repair program
		Unauthorized penetrate to the system	Inadequate hydraulic capacity	Repair and replacement plan for broken or old age part of the network
		Frequency of leak detection program and maintenance plan is less than standard	Troubles in fire fighting system	Detection plan to illegal penetrate to the system and try to control this case.
		High external loading on the pipelines and low internal pressure in the network that cause breaks and cracks in the pipelines	Low operational pressure	Monitor construction and installation process of the pipelines, trench and bedding.
		Bad bedding conditions that cause breaks and cracks in the pipelines		

Table 15 Disinfectant residual in quality critical node

Node : water network (Quality critical node) Microbial indicators				
Parameter: Disinfectant residual (decrease in DR indicates contamination problem in the system) chemical indicator				
Guide words	**Deviation**	**Causes**	**Consequences / Undesired events**	**Responses**
More	D > Minimum residual	Over-dosing of disinfectants in the system Low level of contamination and biofilm in the system	Deterioration in taste and/or odor of the water Heath risk for the customers because of high rate of disinfectant presence in the water	Proper and regular monitoring and controlling of the doses
Less	D < Minimum residual chlorine of 0.2 to 0.5 mg/l [13].	Low dosing of disinfectants in the system Water contamination due to ineffective treatment process Water contamination during distributing due to cross connection between sewage source and water line, low pressure of the network, cracks and breaks in the pipes and others. Biofilm presence that exert chlorine demand and decrease DR	Heath risk for the customers because of active bacteria and microbes in the water Customers must pay for household chlorination	Proper and regular monitoring and controlling of the doses Proper and regular maintenance and repair plans for the system Household chlorination (solutions or tablets in the home) that must be supported by health and hygiene education and risk reduction Control of treatment processes to reduce disinfectant demand

Note for table.15:

In water supplies which are chlorinated there should always be a minimum of 0.5mg/l residual chlorine after 30 minutes contact time in all points in piped supply, This means that a chlorine residual of about 1mg/l when water leaves the treatment plant is needed, in tanker trucks, at filling 2.0mg/l (51)

Table 16 Total and fecal coliforms in quality critical node

Node : water network (Quality critical node) Microbial indicators				
Parameter : Total and Fecal coliforms				
Guide words	**Deviation**	**Causes**	**Consequences / Undesired events**	**Responses**
More	TC & FC > acceptable value	Fecal contamination due to Opening or failure in reservoir or main storage tank, breaks in the pipeline , cross connection between sewage source and water line, or during repairs, reconstruction works, installation new branch in the network.	Deterioration of quality parameters of water in the network	Proper and regular maintenance and repair program for the system
		Bacterial pathogens	Biofilm production	Proper and regular maintenance and repair program for the treatment plant
		Ineffective treatment	High required doses of disinfectants	Household chlorination process
		Presence and growth of Biofilm	Deterioration in taste and odor	Regular flushing and cleaning for the system
		Breaches in the distribution network	Need for household chlorination process (customers must pay for this)	
		Inadequate or loss of disinfectant residual	Health risk for the customers	
		Backflow event		

Table 17 PH in quality critical node

Node : water network (Quality critical node) Chemical indicators				
Parameter: PH (Indication for the metal contamination and corrosion problem) chemical indicator				
Guide words	**Deviation**	**Causes**	**Consequences / Undesired events**	**Responses**
More	PH > 8	Leaching calcium carbonate from cement-lined pipes or tanks into water [11]	Deterioration of quality parameters of drinking water in the network Unacceptable turbidity values of the distributed water	Use proper kind of pipelines.
Less	PH < 7 [11]	Potential contamination problem	Potential corrosion problems	Proper and regular maintenance and repair program for the system
		Backflow event	Corrosion control efforts will be less effective	Proper and regular maintenance and repair program for the treatment plant
		Leaching of some metal and organic chemicals from the pipes such as Lead, Cadmium or Arsenic due to main breaks	Corrosion in the inner surface of the pipelines	Regular flushing and cleaning for the system
		Corrosion in the pipelines	Aging materials and changing their properties	
		Biofilm growth	Lead and copper action level is exceeded	

Table 18 TOC/DOC in quality critical node

Node : water network (Quality critical node) Chemical indicators in water tank				
Parameter: TOC/DOC (Total and dissolved organic carbon) chemical indicator				
Guide words	**Deviation**	**Causes**	**Consequences / Undesired events**	**Responses**
More	TOC/DOC > acceptable level (0.02-0.2) mg/L	Failure in reservoir or main storage tank	Deterioration of microbiological parameters (Coliform growth) of distributed water	Proper and regular maintenance and repair program for the system
		Contamination because of breaks and cracks in the pipelines	Biofilm production	Proper and regular flushing and cleaning for the network
		Contamination during repairs, reconstruction works or installs new branch in the network.	Deterioration in taste and odor of the water	Household chlorination process
		Cross connection between sewage source and water line	Health risk for customers	Control of disinfection processes
		Intrusion		
		Existence of Biofilm in the pipeline		

3.3.3 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

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

3.4 Risk estimation for UE_ Low operational pressure

Low pressure in IWS system may occur because of:

- Low water flow in the network
- High rate of water withdraw from a limited capacity network in a short period, so hydrodynamic operational pressure will decrease under its designed values.
- Low supplied pressure value in transmission main.

Low operational pressure and short supply period force customers to use households' pumps to meet the required pressure and to use roof tanks to store as much water as they can during supply hours to use it later during interruption hours, these pumps and tanks increase the problem because they increase rate of water withdraw during supply period.

3.4.1 Fault Tree analysis for UE

As mentioned before in the section 2.2.3.2, fault Tree analysis is normally carried out in the following steps:

3.4.1.1 System and boundary conditions definition

All detail about studied system; the boundary conditions, initial state of the system and operating conditions are mentioned in section 3.1

3.4.1.2 Top event selection

UE_ Low operational pressure is the particular failure mode to analyze (Top event), section 3.4.1 describe WHAT the undesired event is and WHEN it happens.

Table.19. presents the criteria for each water system components that affect the UE_ Low operational pressure in intermittent water supply system

Table 19 Criteria in each system component

System components	Criteria affect the UE_ Low operational pressure
Water sources	Depletion in water sources with no alternative sources available Alternative or additional water sources available with no financial ability to invest them Available water sources is unacceptable health-based water quality standards and the available treatment plants are inefficient or with no enough capacity. (Next subsystems are unable to compensate)
Treatment plants	(No raw water quantity failure) The water produced from treatment plant is less than demand due to: Plant production capacity less than required with no financial ability to increase it Technical or technological failure in the plant with no regular maintenance, repair or rehabilitation plans Treatment plant produce enough quantity of water but with unacceptable health-based water quality standards (Next subsystems are unable to compensate)
Pumping station	(No treatment plants quantity or quality failure) The pumping station capacity is less than required for available water and no financial ability to increase the capacity of the system Technical failure in available pumps Inappropriate operational schedules Part of the system is out of service with no rehabilitation, maintenance or replacement plan and no budget available (Next subsystem are unable to compensate)
Electricity power resource	(No treatment plants or pumping station failure) Frequent electricity power failure with no or insufficient redundancy power system available Interruption period because of electricity rationing strategy (Next components are unable to compensate)
Effect of operation mode, water network status and consumers behaviors on the system	(Failure in one or more previous components that force water company to operate as intermittent water supply) Factors aggravate the impacts of intermittent water supply: OPERATION MODE & OTHER REGULATIONS: Inappropriate operation manner and supply schedules such as Duration and frequency of supply, Maintenance and repairs plans, Budget allocation Water tariff DISTRIBUTION SYSTEM Technical failure that are not detected or detected but with no reactions (repairs, maintenance or rehabilitation plans) Poor materials and/ or old age of the pipelines with no reconstruction or rehabilitation plans No or irregular flushing program to the network Rapid urbanization and need to cover the new demand from existing network CONSUMERS They store as much water as they can during limited period of supply Their demand is based on the storage tanks capacity They choose the household pumps without any hydraulic background (most of them use pumps with characteristics more than required and that affect the other consumers)

3.4.1.3 FT diagram construction

All immediate, necessary and sufficient causes (Events) 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.

Each event in level ($level_i$) is considered sub-top event when processing the next level ($level_{i+1}$), Fig.26

The proposed fault tree diagram doesn't have MOE (Multiple occurring events)

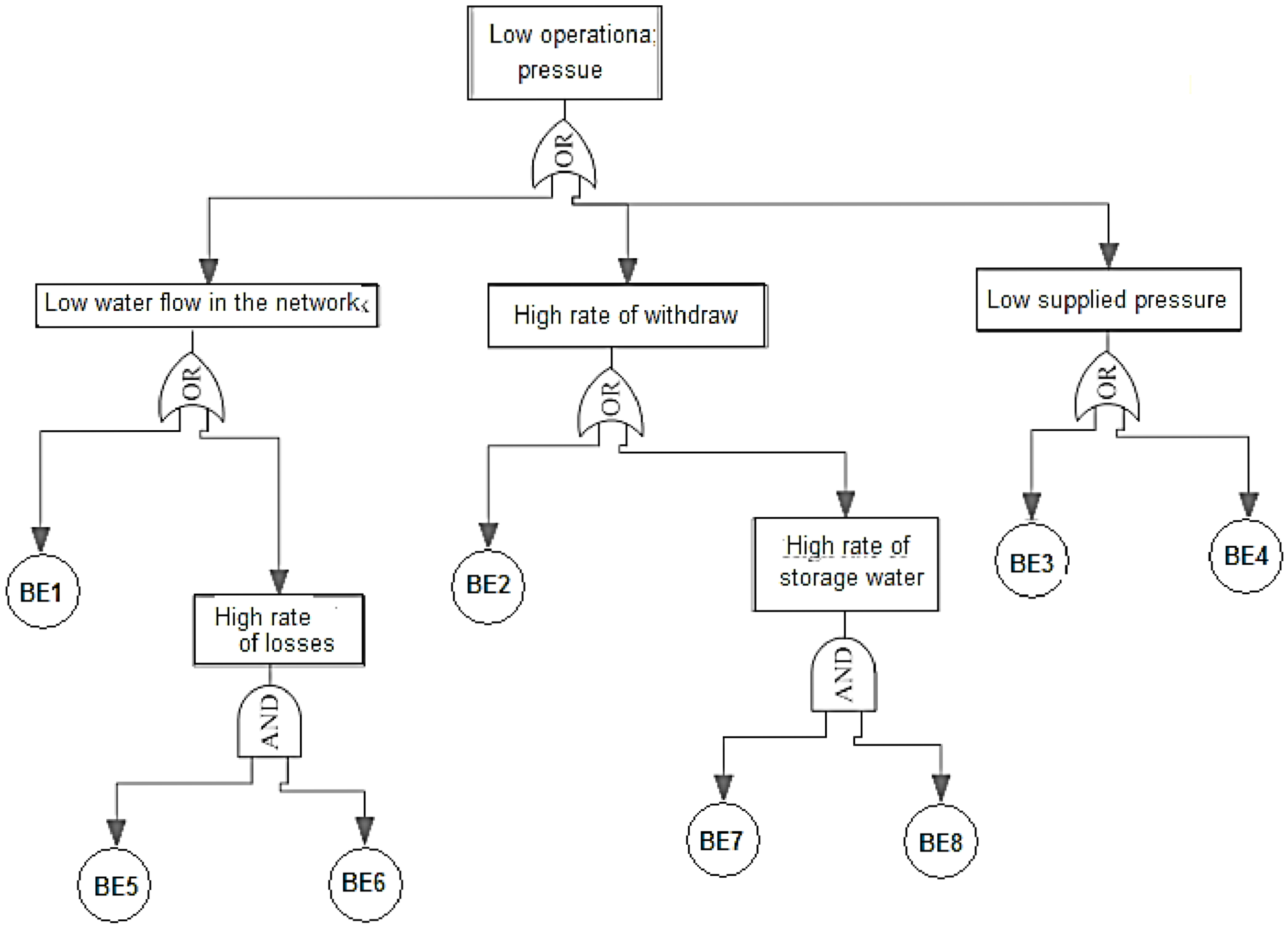


Fig. 26 Schematic fault tree for UE_ Low operational pressure in IWS system

3.4.1.4 Basic Events description

- $\boldsymbol{BE_1}$ _Supply failure

BE_1 is any water supply value S less than a critical value (required or designed)S_c.

That could happen because of one or more of the following:

- Decreasing in annual precipitations compared with normal precipitation
- Degradation in groundwater levels with no ability to compensate it during the years.
- Reduction in the minimum water flow in rivers or degradation in the water level in lakes or reservoir
- Biological or chemical contaminations access to the water source and the quality becomes unacceptable to use it for drinking or domestic purposes with inadequate treatment plant capacity or inefficient to deal with new contamination
- Seawater intrusion into the groundwater due to high withdraw rate from the wells
- Failure in distribution sub-system

- $\boldsymbol{BE_2}$ _ Demand failure

BE_2 is water demand value D more than critical (designed) value D_c

That could happen because of one or more of the following:

- Rapid or unplanned urbanization, new districts and buildings are built or/and predicted and they will loaded on the existing water and electricity networks that could overload some nodes in the network.
- Population growth, estimated population growth rate in Middle East and Africa is between (40-50%), according to United Nations statistics between 1990 and 2010
- Increasing in consumers' demand because of the weather, the seasons and the life type of people, etc.

- $\boldsymbol{BE_3}$ _Technical failure

BE_3 is any failure could happen to the pumping system and cause partially or fully disable in water supply process.

- $\boldsymbol{BE_4}$ _Electrical failure

BE_4 is a power interruption because of rationing strategy or of any failures that could happen in the electrical power supply system and cause partially or fully disable in water supply process.

- $\boldsymbol{BE_5}$ _Pipelines & equipment failure

$\mathrm{BE_5}$ is any failure that could happen in any equipment or main pipeline in the network and cause partially or fully disable in water supply process or cause increasing in the real water losses more than the allowed value.

- $\boldsymbol{BE_6}$ _ high water losses

$\mathrm{BE_6}$ is any apparent losses more than allowed value

Top down audit to estimate water losses (52):

- Determine the amount of water supplied to the system, typically for a one year period,
- Determine authorized consumption (billed + unbilled), and
- Calculate water losses (water losses = system input – authorized consumption)
- Estimate apparent losses (unauthorized consumption + customer meter inaccuracies + billing errors and adjustments)
- Calculate real losses (real losses = water losses – apparent losses)

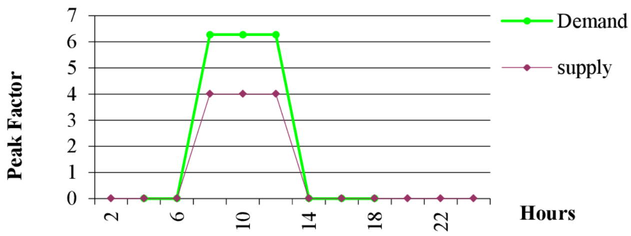
- $\boldsymbol{BE_7}$ _ Duration of supply

$\mathrm{BE_7}$ is the duration of supply under critical value t_c (t_c could be 8 or 10 hours) and that depends on rationing plan of water utility.

When the duration of supply is short so the consumers are forced to collect and store water in the same short period of time, all pumps works in the same time and that increase velocity in the pipelines and decrease pressure and hydraulic capacity of the network.

When duration of supply is decreasing↓, the rate of withdraw is increasing ↑ as shown in Fig.27 and the pressure is decreasing ↓

In general the water total volume of supplied water is fixed; the duration of supply affects the hourly Qs



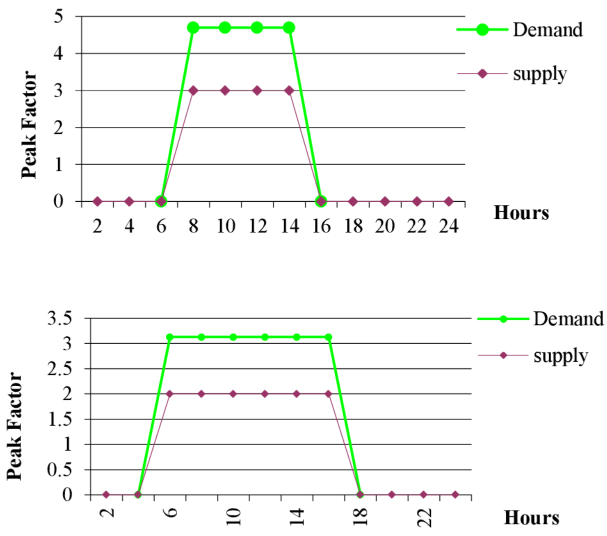


Fig. 27 Supply and demand patterns during a period of 6 or 8 or 10 hours

- $\boldsymbol{BE_8}$ Storage unit characteristics failure

BE_8 is the case of using household pumps with performance higher than recommended and a storage tank with capacity larger than recommended.

Recommended capacity is calculated per capita:

Daily demand 100 liter/capita, family of 5 persons, the demand is 500 liter/family/day, if the water is available 3 days a week so the stored volume should cover 2 days, it should be about 1000 liter and that required average storage tank.

3.4.1.5 Restrictions on FTA diagram

Previous FT diagram Fig.26 is applied with the following restrictions:

1. 1st OR gate is always OR gate
2. 2nd OR gate is still OR If High rate of losses ≥ 40% Total supplied water, else it will be AND gate between two components as follow:

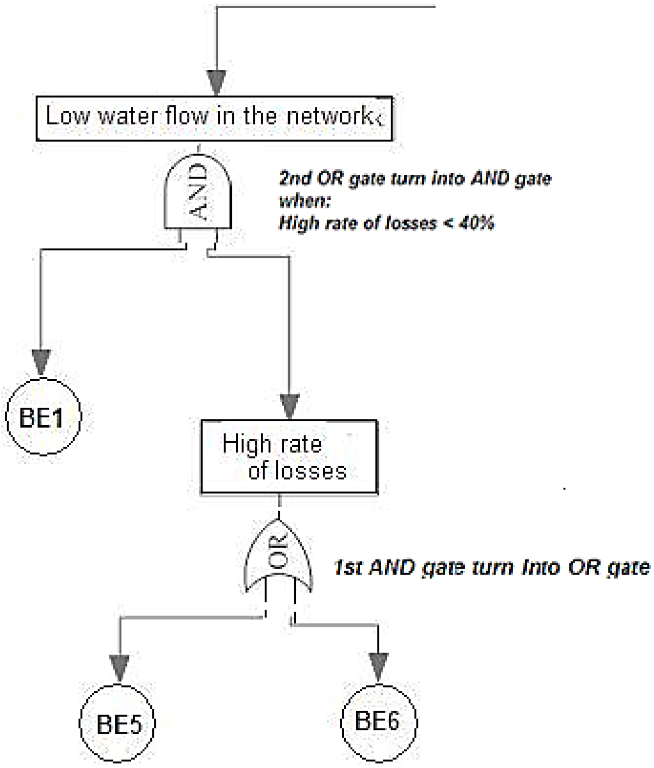


Fig. 28 Restriction of 2nd OR gate

3. 3rd OR gate still OR gate If the increasing in water demand ≥ critical value, else it will be AND gate

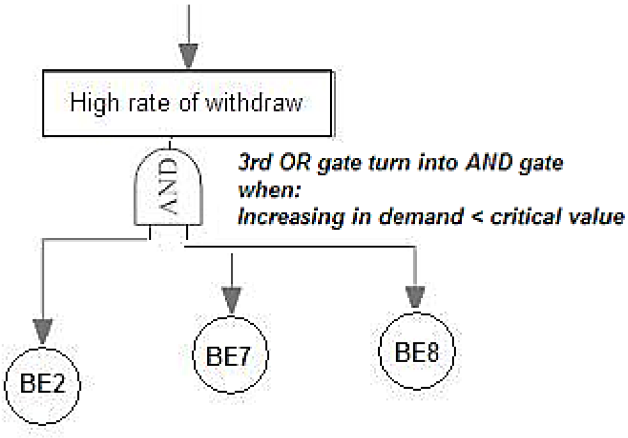


Fig. 29 Restriction of 3rd OR gate

4. 4th OR gate is always OR gate
5. 1st AND gate is still AND If apparent losses (Unauthorized penetrate to the system component) ≤ 40% from total water losses, else it will be OR gate between two components as following:

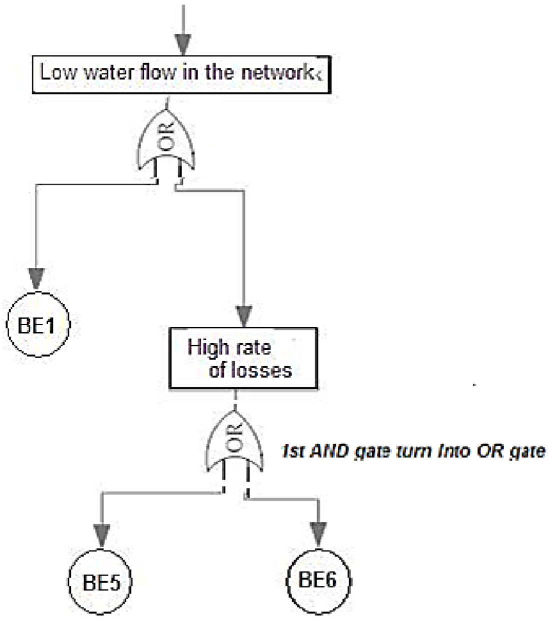


Fig. 30 Restriction of 1st AND gate

6. 2nd AND gate is always AND

3.4.1.6 FT evaluation

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

To simplify FT diagram, all basic events are considered independent.

FT 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 (34)

Once the fault tree has been drawn, it can be evaluated to yield its qualitative and quantitative characteristics, these characteristics can be obtained from the equivalent Boolean equations (34).

- OR-gate:

The OR-gate is equivalent to the Boolean symbol “+”

$$E_1 \text{ OR } E_2 = E_1 + E_2 = E_1 \cup E_2 \qquad 13$$

Where

E_1, E_2 are events

If two events E_1 and E_2 are not mutually independent:

$$\mathrm{P}(\mathrm{E}_1 \cup \mathrm{E}_2) = \mathrm{P}(\mathrm{E}_1) + \mathrm{P}(\mathrm{E}_2) - \mathrm{P}(\mathrm{E}_1 \mathrm{and} \mathrm{E}_2)$$

$$P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1).P(E_2/E_1) \qquad 14$$

For n events, $E_1, E_2, \ldots\ldots, E_n$ general formula can be expressed:

$$P(E_1 + E_2 + E_3 + \cdots + E_n) =$$
$$\sum_{i=1}^{n} P(E_i) - \sum_{i=1}^{n-I} \sum_{j=I+1}^{n} P(E_i and E_j) + (-1)^n P(E_1 and\ E_2 and \ldots . and E_n) \qquad 15$$

If we ignore the possibility of any two or more of the events E_i occurring simultaneously, the equation are reduced into:

$$P(E_1 + E_2 + E_3 + \cdots \ldots + E_n) = \sum_{i=1}^{n} P(E_i) \qquad 16$$

This event is so-called „rare event approximation” that is play an important role in fault tree quantification (34).

If E_1 and E_2 are mutually exclusive then $P(E_1\ and\ E_2) = 0$

If E_1 and E_2 are independent then $P(E_1\ and\ E_2) = P(E_1).P(E_2).$, $P(E_1 and E_2)$ is small compared with $P(E_1) + P(E_2).$, so that we can use rare event approximation Equ.16.

If E_2 are completely dependent on E_1 then $P(E_1/E_2)$=1 $\Longrightarrow P(E_1\ and\ E_2) = P(E_1)$

- AND-gate :

The AND-gate is equivalent to the Boolean symbol "."

$$E_1 \; and \; E_2 = E_1 \cdot E_2 = E_1 \cap E_2 \qquad 17$$

Consider now two events E_1 and E_2 that are not mutually independent, they are interdependent, in order to treat events like this nature, we introduce a concept of conditional probability, we need a new symbol $P(E_1/E_2)$, which is the probability of E_2, given E_1 has already occurred.

$$P(E_1 \cap E_2) = P(E_1).P(E_2/E_1) \qquad 18$$

For n events, $E_1, E_2, \ldots, E_n$ general formula can be expressed:

$$P(E_1.E_2 \ldots .E_n) = P(E_1).P(E_2/E_1).P(E_3/E_1 and E_2) \ldots P(E_n/E_1 .. and E_{n-1}). \qquad 19$$

If E_1 and E_2 are mutually independent, then $P(E_1/E_2) = P(E_1)$ and $P(E_2/E_1) = P(E_2)$ the equation will be:

$$P(E_1 . E_2) = P(E_1).P(E_2) \qquad 20$$

For n events:

$$P(E_1 . E_2 .. E_n) = P(E_1).P(E_2)..P(E_n) \qquad 21$$

3.4.1.7 The minimal cut sets

A minimal cut set is a unique set of events that together cause the UE to occur, it consists one or many events.

The minimal cut set expression for the UE can be written in general form Equ.22:

$$TOP = M_1.M_2 \ldots .M_k \qquad 22$$

Where

TOP 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) and hence the general n-component minimal cut set can be expressed Equ.23

$$M_k = E_1 . E_2 .. E_n \qquad 23$$

We can determine the cut sets of the FT by following the steps:

- The tree is first translated to its equivalent Boolean equations, Equ.13 and Equ.17

- Either the top-down substitution method (we start with the top event equation then substitute and expand using Boolean laws Equ.24,25,26 and 27 until the minimal cut set for the top event is obtained) or bottom-up substitution method is used

The distributive law

$$E_1 \cdot (E_2 + E_3) = E_1 \cdot E_2 + E_1 \cdot E_3 \quad 24$$

$$E_1 + (E_2 \cdot E_3) = E_1 + E_2 \cdot E_1 + E_3 \quad 25$$

The absorption law

$$E_1 \cdot (E_1 + E_2) = E_1 \quad 26$$

$$E_1 + E_1 \cdot E_2 = E_1 \quad 27$$

Minimal cut set for the proposed fault tree diagram in general case, Fig.26;

$$T = OR_2 + OR_3 + OR_4$$

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

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

$$= M_1 + M_2 + M_3 + M_4 + M_5 + M_6 \quad 28$$

For other cases of diagram, we have to substitute the gates with events using the equations: 13, 17, 24, and 25 for example:

IF 2nd OR gate turned into 3rd AND gate Fig.28, the minimal cut set:

$$T = AND_3 + OR_3 + OR_4$$

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

$$= BE_1.(BE_5.BE_6) + BE_2 + (BE_7.BE_8) + BE_3 + BE_4$$

$$= M_1 + M_2 + M_3 + M_4 + M_5 \quad 29$$

In our case, all minimal cut sets M_i are independent and we ignore the possibility of any two or more of the events M_i occurring simultaneously, the equation are reduced into rare event approximation (Equ.16) if the probabilities of the events are small enough:

$$P(TOP) = P(M_1 + M_2 + M_3 + \cdots + M_n = \sum_{i=1}^{n} P(M_i) \quad 30$$

Or we use minimal cut set upper bound

$$P(TOP) = 1 - \prod_{i=1}^{n}(1 - P(M_i)) = 1 - [(1 - P(M_1)).(1 - P(M_2)) \dots .(1 - P(M_i))] \quad 31$$

To calculate the probability of top event according to general case of tree, Equ.31

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

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

$$P(TOP) = 1 - [(1 - P(BE_1)).(1 - [P(BE_5).P(BE_6)]).(1 - P(BE_2)).(1 - [P(BE_7).P(BE_8)]).(1 - P(BE_3)).(1 - P(BE_4)] \quad 32$$

3.4.2 Probability analysis

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

- Non-repairable basic events:

$$P(BE_i) = 1 - e^{-\lambda.t} \quad 33$$

- Repairable basic events:

$$P(BE_i) = \lambda.t/(1 + \lambda.t) \quad 34$$

Where

λ is an event failure rate (1/hour)

t is exposure time or repair time (hour)

$$\lambda = 1/MTBF \quad 35$$

Where

MTBF is the Mean Time between Failures (hour)

FT's deal with small numbers for example: $(< 1.e^{-6})$ means one failure per million hours

To simplify the calculations we can combine the repairable and non-repairable events and use one equation Equ.34 to calculate the probability considering t is exposure or repair time.

The major problem is always how to calculate or estimate the value of probabilities and consequences under uncertainty – Lack of data, insufficient historical records and/or unreliable data, uncertainty of failure detection, uncertainty of employed methodology of risk analysis and proper interpretation, etc. Using a combination of hard data and experts judgments as inputs to estimate the probabilities of events of the fault tree and consequences could be useful, Lindhe (53).applied fault tree method for integrated and probabilistic risk analysis of drinking water system, he used hard data and experts judgments as input and modeled the variables using Beta and Gamma probability distributions and performed the calculations by means of Monte Carlo simulations

Insufficient available data may be effectively sometimes solved, by using frequency instead of mathematical probability of occurrence by using categorization of probability of occurrence, severity of consequences based on some chosen factors or indicators, and on limits of categories, that will be done by discussion with experts in water utility and collecting available data (4).

Also some studies described that evidence theory/Dempster-Shafer (DS) theory approach is very useful to express uncertain judgments of experts; the DST calculus describes the subjective viewpoint as an assessment for an unknown objective fact (36).

The data needed for the fault tree analysis is based on:

1. Hard data (e.g. measurements and statistics on events),
2. Experts judgments and
3. Combinations of both previous options.

3.4.2.1 Basic events analysis under Complex Methodology

Hard data is available:

1. Specify variable for the BE,
2. According to available hard data we can choose the appropriate probability distribution (density function $\mathrm{f(t)}$) for each $\mathrm{BE_i}$ 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 TBFs the time between failures using equation Equ.36

   $$TBF = Step * n \tag{36}$$

   Where

   n is the number of 0 codes between two sequential 1 codes
8. Calculate t the exposure time (downtime) using the equation Equ.37

   $$t = Step * ration * m \tag{37}$$

   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 MTBF and t under uncertainty, Equ.38

   $$MTBF = average(TBF)$$

   $$t = average(t) \tag{38}$$
10. Distinguish between repairable and non-repairable events to choose the suitable equation Equ.33 or Equ.34 and estimate the probability

3.4.2.2 Basic events analysis under Simple Methodology

Hard data is NOT available:

1. Estimate the probabilities under uncertainty using Dempster-Shafer theory section 2.2.3.4 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.34
   - Estimate $m_1(N)\ and\ m_2(N)$
   - Calculate $m_1(Y,N)\ and\ m_2(Y,N)$

   $$m_i(Y,N) = 1 - [m_i(Y) + m_i(N)] \quad 39$$
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 Equ.10 because it handles with the conflict between data sources if there is any.

6. Arrange the calculations in a table as follows :

Table 20 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}	$m_1(Y,N)$	$m_1(Y,N)\times m_2(Y)$	$m_1(Y,N)\times m_2(N)$	$m_1(Y,N)\times m_2(Y,N)$
$\sum_{p_a \cap p_b = p_i} m_1(p_a).m_2(p_b)$				
m_{1-2} (combination rules)				

7. Calculate the Estimate Value $Bet(Y)$ Equ.40 which is equal to the estimated probability value of occurrence

$$P_i(BE_i) = Bet(Y) = \frac{m_{1-2}(\{Y\})}{1} + \frac{m_{1-2}(\{Y,N\})}{2} \quad (40)$$

3.4.3 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 (6).

The consequences of failures are defined by the number of people affected; they are included in the Fault tree analysis Equ.41

$$\mathrm{R} = \mathrm{P_F}.\,\mathrm{C} \qquad (41)$$

Where

P_F is the probability of failure

C is the number of consumers affected.

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.42

$$R = \sum_{i=1}^{n} P(M_i).\,C_i \qquad (42)$$

Where

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

4 CASE STUDY

4.1 System description

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.

To compensate insufficnet provided water, some consumers are forced to fullfill thier household storage tanks from private sources by tanker trucks, which bring the drinking water from near towns or valid sources.

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.

4.1.1 Water source

The main water source for the network is a group of wells, 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

The water is pumped from three wells into water tower across Iron pipeline

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

4.1.2 Distribution system

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.

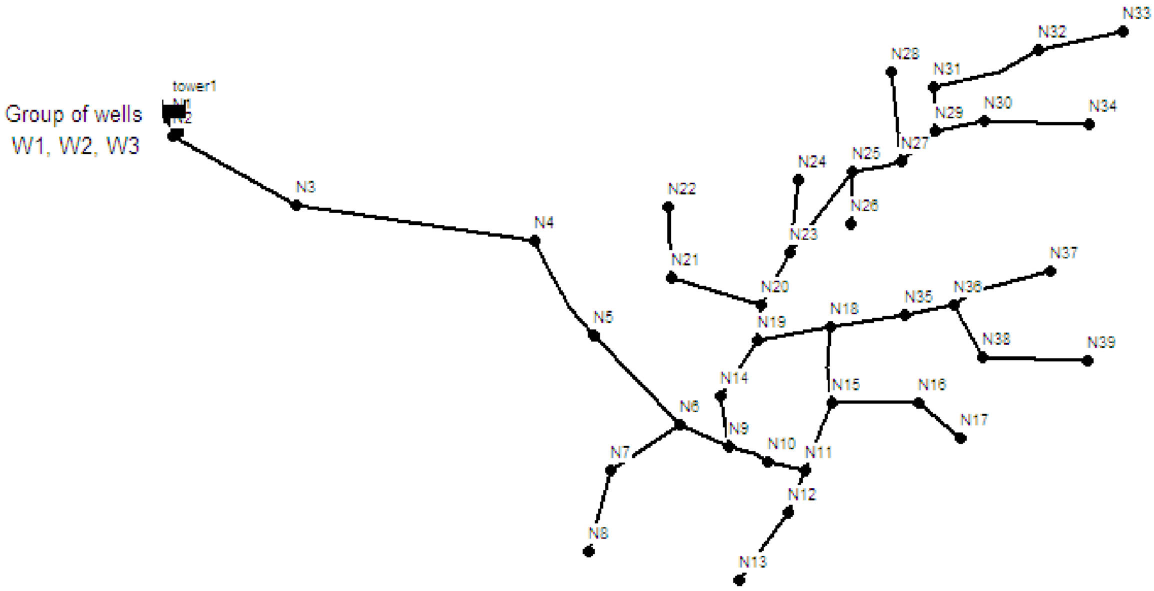


Fig. 31 Water distribution network scheme

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

Household water storage unit is provided for each flat in the building as detailed in section 3.1.1, while the household water pumping system is provided for the whole building (central pump for a building) this assumption simplify the network model by Epanet 2.

About the 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, the water supply pattern shown in Fig.1

4.2 Data process

For the studied water system, I proposed two different data process:

1st when data is available (CRAM), the outputs are evaluated using 5-years old database collected in the town.

The available hard data are:

- Supply patterns and known problems for last five years.
- Available customers meters reading in the last five years.
- Information of the frequency of electrical power cut and records of failures.
- Maintenance, repairs and cleaning plan: documentation of implemented maintenance plan and frequency, cleaning works plan, and duration of repairs.
- Available records of failures: pipelines, valves, technological and technical failures for last five year.
- Buildings documentation: current and future expected projects within 5 years.
- Highest and lowest temperatures, climate in the region.
- Old used technologies.
- Analysis of the distributed water in the last 5 years.
- Survey pipelines
- Technical information about valves: valves types, casting year, replacement records, locations, technical state and maintenance frequency.
- The technical condition of the pumps, in addition to information about the previous failures and repairs.
- Information about the end-users (consumers)

2nd when previous data is not available (SRAM), the data sources (experts judgments) will be employed

Fig.26 illustrates a schematic fault tree including the main type of events that may cause Low operational pressure in intermittent water supply system; this will be used in our case study with some modifications if it is required.

Basic event divided into repairable and non-repairable events, the equations Equ.33 and Equ.34 for non-repairable and repairable are applied to calculate basic events probabilities.

Table 21 Events' types

BEi	Event type
Supply failure	Non-repairable
Demand failure	Non-repairable
Technical failure	Repairable
Electrical failure	Repairable
Pipelines and equipment failure	Repairable
Apparent losses	Non-repairable
Duration of supply	Non-repairable
Storage unit failure	Non-repairable

For both types of events the required variables are failure rate λ and the downtime or repair time t, Fig.32.

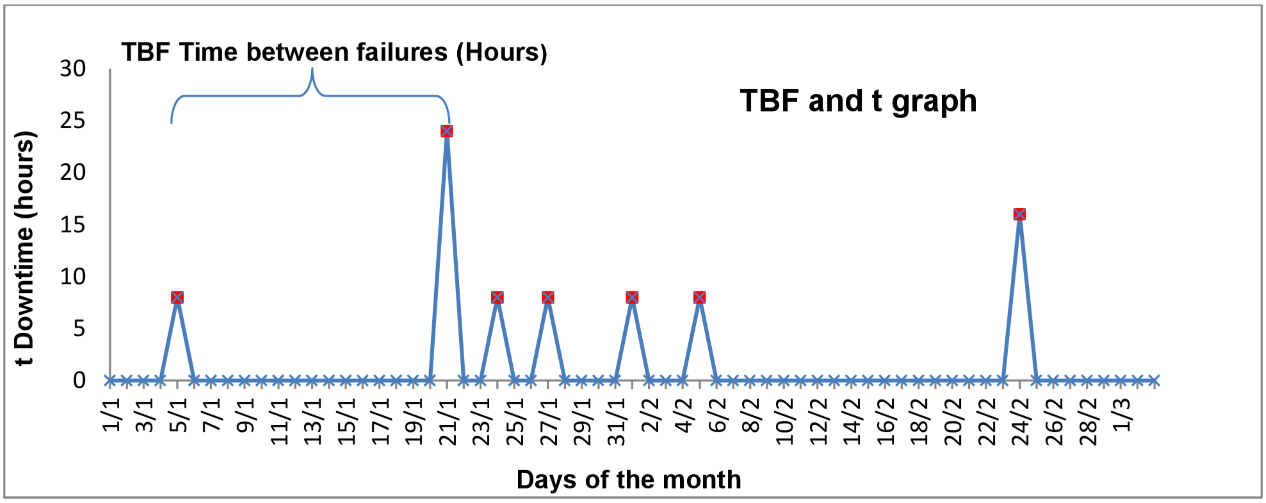


Fig. 32 TBF and t graph

As mentioned in section 3.4.3, we will deal with all events in Table.21 as repairable.

4.2.1 Complex Methodology outputs

Data process under CRAM is mentioned in section 3.4.3.1

Monte Carlo method was be implemented to fulfill the missed data values when data is not completely available

In section 3.4.2.4 all basic events described, and all required variables are mentioned, in this case study some more details about BE4 and BE8 should be taken into account in the calculations:

- BE4 Electrical failure could be:
    1. Rationing plan and/or
    2. Failures in the power system.

  In this town, daily rationing plan in general estimated by 2, 4 or 6 hours/day, it may be changed according to the seasons or location.

- BE8 Storage unit failure helps and encourages customers to store as much water as they can NOT as they need, it is not temporal (it doesn't change with time).

  We can estimate the value $P(BE_8)$ by making questionnaire about the household storage systems in the town.

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 22 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 23 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

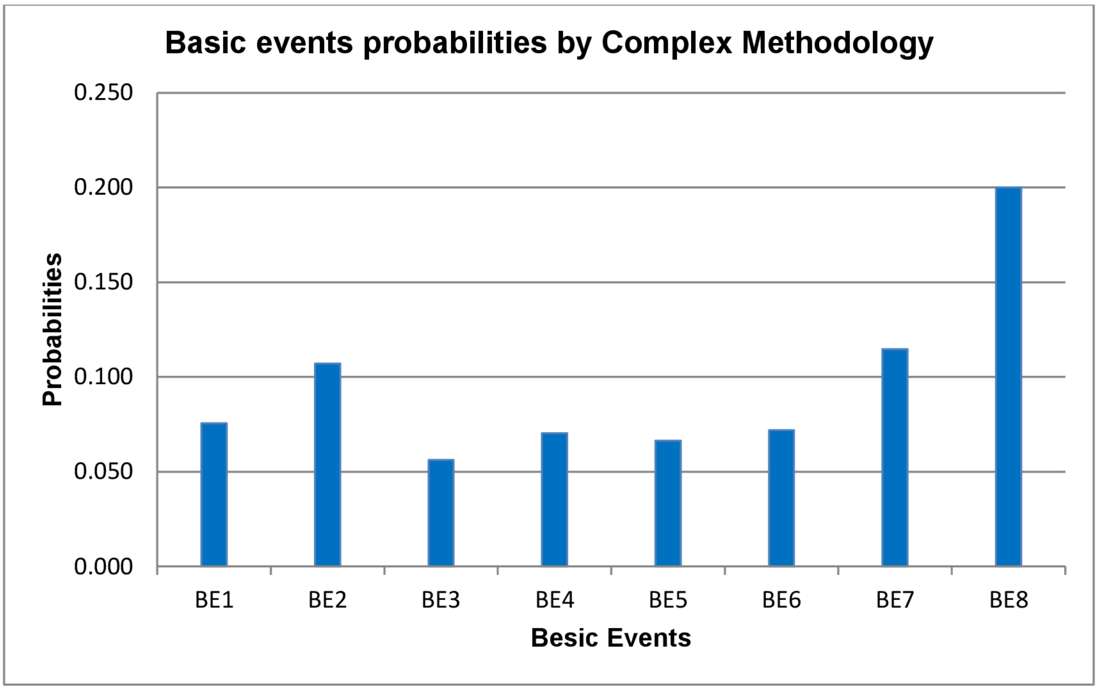


Fig. 33 Basic events probabilities by CRAM

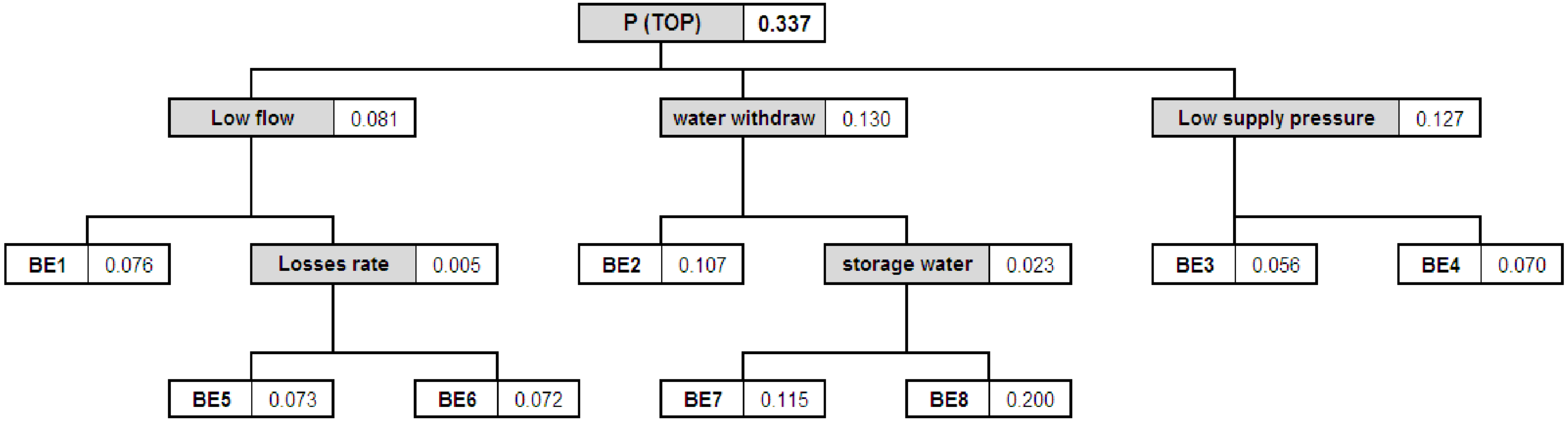


Fig. 34 Fault tree calculation under CRAM using Equ.30

Table 24 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		

Apply the equation Equ.32,

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

$$P(TOP) = 1 - [(1 - 0.076).(1 - [0.066 * 0.072]).(1 - 0.107).(1 - [0.115 * 0.200]).(1 - 0.056).(1 - 0.070]$$

$P(TOP) = 0.296$

To calculate risk level, Ci is the number of all consumers affected

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.42

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

$\mathrm{R} = 2287$ 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.

4.2.2 Simple Methodology outputs

Data process under SRAM is mentioned in section 3.4.3.2, as an example of the calculations I present the following table of BE1

Table 25 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 26 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 27 Belief, estimate value and Plausibility of the basic events

	Min.	Expected	Max.
	Bel(BEi)	**Bet(BEi)**	**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

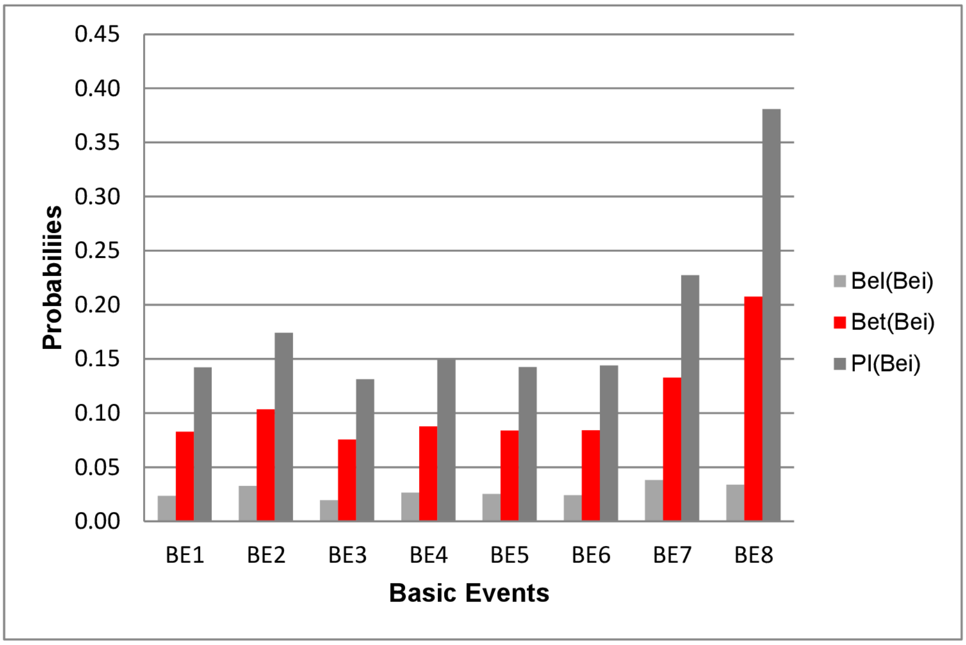


Fig. 35 Belief, estimate value and Plausibility of the basic events

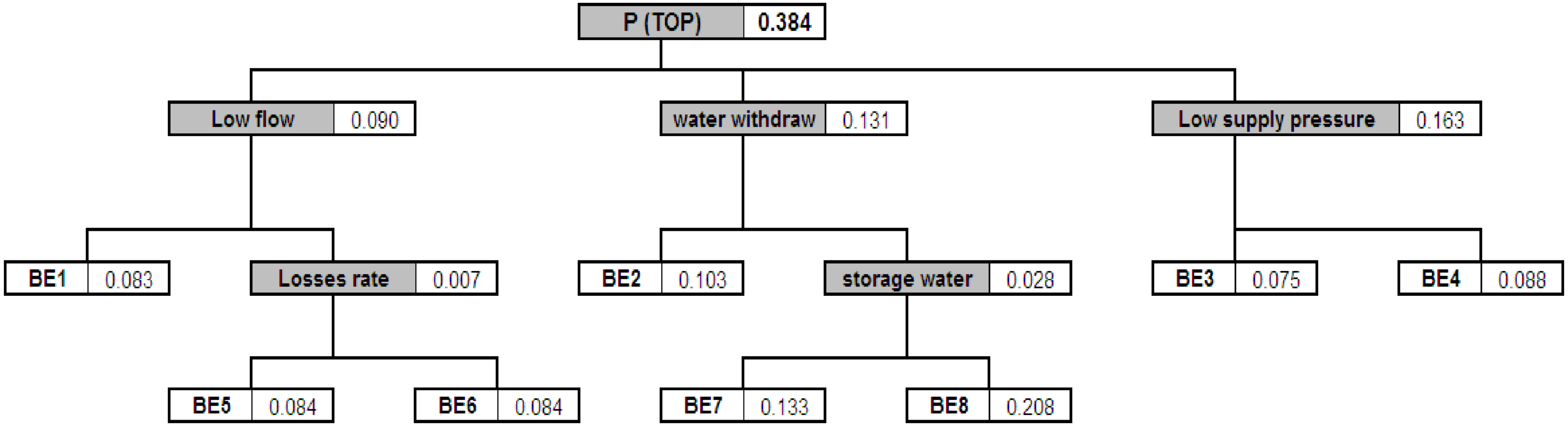


Fig. 36 Fault tree calculation under SRAM using Equ.30

Table 28 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		

Apply the equation Equ.32,

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

$$P(TOP) = 1 - [(1 - Bet(BE1)).(1 - [Bet(BE_5).Bet(BE_6)]).(1 - Bet(BE_2)).(1 - [Bet(BE_7).Bet(BE_8)]).(1 - Bet(BE_3)).(1 - Bet(BE_4)]$$

$$P(TOP) = 1 - [(1 - 0.083).(1 - [0.084 * 0.084]).(1 - 0.103).(1 - [0.133 * 0.208]).(1 - 0.076).(1 - 0.088]$$

$$P(TOP) = 0.330$$

Probability of failure represents the proportion of time the system is in failure mode for example, the expected number of days per year at least one consumer is exposed to quantity or quality failure

To calculate risk level, Ci is the number of all consumers affected.

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.42

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

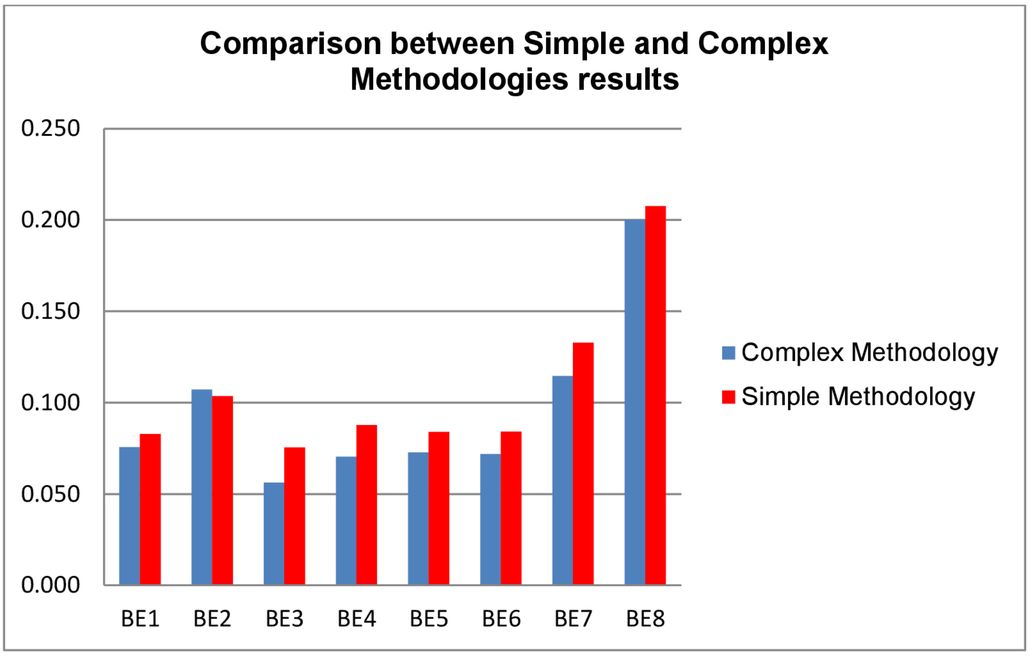
$\mathrm{R} = 2608$ min

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

4.3 Results and discussions

Simple methodology gives higher output values than Complex one because mi(Y,N) has high effect on the final result

Fig. 37 Comparison between SM and CM results



To have more accurate results when implementing DS theory, I suggest the experts to assume mi(N)> 80%

The results show that the difference between Complex and Simple is about 321 minutes per year, and error is $6 * 10^{-5}$, extra 6 hours of failure for each 10000 hours of study, SRAM gives higher output values than CRAM one.

Risk reduction options for this case study:

- Budget allocation for pumping system maintenance and repair programs.
- Budget allocation for water resources management projects to find additional resources: Surface water, underground water or to treat or desalinate available water
- Water resources allocation
- Emergency response plan to any failure in existing pumping system, reservoir, treatment plants, and distribution system
- Redundancy pumping system

- Reduce and control water losses by applying efficient strategies to detect leaks and take speed and efficient reactions as speed repairs or replacement of damage part and control illegal penetrate to the system
- Control households tanks and pumps: Monitor storage tanks' volumes and pumps characteristics
- Increase the duration of supply to decrease the withdraw rate, increase the hydraulic capacity of the network and to affect consumers behaviors
- Redundancy electrical power supply: Find alternative electrical power sources
- Regular maintenance and flushing program: Clear and regular inspection, maintenance, repair, cleaning and flushing plans should be set to the equipment and pipelines.
- Public awareness programs

5 CONCLUSION

5.1 The findings and results of the project

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.

Many undesired events in the developed list are in common between continuous and intermittent water supply systems, but with difference causes, consequences, and criteria of probability

Risk Analysis Methodology for IWS system was proposed in this study, the generic framework Fig.22

Two different cases of probability analysis procedure were built up to estimate BEs probabilities under uncertainty, one gives out acceptable accurate values of outputs by using available hard data and employing Monte Carlo simulation and the other gives out an indication of risk level of the system by using DS Theory which could be useful in developing countries conditions where no available records or data for adequate number of years exists.

The study confirmed that an IWS system has unstable hydraulic conditions:

- The distribution network is not fully pressurized pipeline network but a network with very low pressures,
- It is a network with restricted water supply hours per day,
- Inequitable distribution of the available water,

- Thousands of roof tank connections,
- In case of fire, unavailable immediate supply.
- Inconvenience to consumers.

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.

HAZOP documents take into account the supposed IWS system, in other case study some modifications should be taken into account:

- The study nodes: we may change or add new study node according to the available reading nodes for the water company that we can take required data
- The parameters: we may add or delete some parameters according to the available data in the company

- The guide words in the tables: we may add more guide words or use other criteria to determine the deviations of the system from standard operating conditions.
- Even if we relied on the same study nodes and tables, the causes, undesired events or the responses may be changed according to the real situation in studied system

Risk level was estimated by using FTA technique in terms of CML Customers Minutes Lost, Equ.42

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.

5.2 Recommendations for future research

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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Principal Symbols and Abbreviations

BE	Basic events
Bel	Belief measure
Bet	Estimate value
Bpa	Basic probability assignment
CML	Customer Minutes Lost
CRAM	Complex Risk Analysis Methodology
CWS	continuous water system
DBPs	Disinfection by-products
DPSIR	Driving force, Pressure, State, Impact and Responses framework
DST	Dempster-Shafer theory
EPANET	Environmental Protection Agency modeling software
ETA	Event Tree Analysis
FEMA	Federal Emergency Management Agency
FEIS	Failure Experience Improvement System
FMECA	Failure Modes, Effects, and Criticality Analysis
FTA	Fault Tree Analysis technique
HACCP	Hazard Analysis at Critical Control Points
HAZID	HAZard Identification Analysis
HAZOP	HAZard and Operability technique
HRA	Human Reliability Assessment
ICI	Imperial Chemical Industries
IWS	Intermittent water supply
LCV	Level Control Valve
MC	Monte Carlo method
MCS	Monte Carlo simulations
MOE	Multiple occurring events
MTBF	Mean Time between Failures

NRC	Nuclear Regulatory Commission
PAHO	Pan American Health Organization
PI	Plausibility measure
PHA	Preliminary Hazard Analysis
PRA	Probabilistic Risk Assessment
PVC	Polyvinyl chloride plastic
RA	Risk Analysis methodology
SF	Safety Function
SRAM	Simple Risk Analysis Methodology
SWMM	Storm Water Management Model
TECHNEAU	Technology Enable Universal Access to safe water
THDB	TECHNEAU Hazard database
TRDB	TECHNEAU Risk reduction options database
UE	Undesired Event
WHO	World Health Organization
WSS	Water Supply System