Development of an approach for the evaluation of wastewater reuse options for arid and semi-arid area

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The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. Appropriate credit has been given where reference has been made to the work of others. The contribution of the candidate and the other authors to this work has been explicitly indicated below:

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In publication I, the candidate planned, and did the writing of the manuscript, FLETCHER, L. & EVANS, B reviewed and provided comments on the manuscripts. The Papers have been used in some sections of Chapter 2, 4, and 6.

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Abstract

Considering water scarcity problem in many arid and semi-arid regions, it is not surprise that wastewater reuse in agriculture increasingly become the most attractive and reliable water source for irrigation. However, in developing countries sustainable wastewater reuse management faces many challenges. including Technical challenges (such as inadequate sanitation capacities and poor wastewater infrastructures and treatment), the lack of complete economic analysis considers all the economic aspects and benefits; many intangible costs and benefits (such as health and environmental effects of wastewater reuse project, regulatory costs, public information and education, and value of water) hardly included in an economic appraisal of wastewater reuse project. Furthermore, there is a lack of implement tools and models for evaluating wastewater management options for mitigating environmental risks associated with chemicals constituents in wastewater which can be used for economic analysis and help decision maker to decide on available reuse strategies under specific environment, social and economic conditions.

This research was attempted to full fit some of these gaps in knowledge. The aim of this research is to develop a novel integrated approach that combine health risk assessment, environmental risk assessment and economic analysis to enhance more sustainable management of wastewater reuse in agriculture. This study is one of few research that bringing the three aspects together; the outcome of the study is a spreadsheet-based model that can be used to assess different reuse strategies and to determine the suitable scale at which treatment alternatives and interventions are possible, feasible and cost effective to optimise the trade-offs between risks to protect public health and the environment and preserving the substantial benefits. The study was based on a case study in Misurata in northern Libya, but it will have relevance to a wide range of arid and semi-arid regions with similar agro-ecological features.

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Chapter 1. Introduction

1.1 General introduction

Water scarcity is a growing concern in many arid and semi-arid countries, especially where the limited natural water resources are heavily exploited. The increase of water scarcity threatens economic development and sustainability of human livelihoods as well as environment especially in developing countries(Scott et al., 2004). The challenges generated by water scarcity will become even greater in future because of growth in population, urbanization, climatic change and growing urban food demand which will contribute to increasing the gap between water supply and demand for water(Hussain et al., 2002). It is estimated that around 40% of the global population in next few decades will live in countries facing water stress(WHO, 2006).

Globally, agriculture is the largest water consuming sector, accounting for approximately 70% of all freshwater extraction (Winpenny et al., 2010). Due to growing competition between the agricultural and industrial sectors and the higher economic value in urban and industrial uses of high-quality freshwater supplies, as result of the increasing demand for water, wastewater has increasingly become the most predominant low cost and reliable alternative to conventional irrigation water in many countries, especially arid and semi-arid regions. Reuse of wastewater in urban and peri-urban agriculture is already a widespread practice in different parts of the world (Jiménez et al., 2010a, Winpenny et al., 2010). It is estimated that at least 10% of the global population consumes foods produced using wastewater irrigation (WHO, 2006). Wastewater can be considered as a reliable source of water and nutrients that is available all year around (Hussain et al., 2002, Jiménez et al., 2010a, Qadir and Scott, 2010). Its availability and its nutrient properties are important factors that make it valuable particularly in arid and semi-arid climates (Jiménez et al., 2010a).

Nevertheless, wastewater reuse has both positive and negative impacts. As a result of its water and nutrient content that are important for crop production, it can generate substantial value to urban and prei-urban agriculture, supporting farmer livelihoods and providing considerable benefits to related communities and the environment (Hussain et al., 2001). On the other hand, the reuse of wastewater particularly untreated or partially treated wastewater may result in substantial risks to public health and surrounding ecosystems as result of microbial and toxic components.

Concern regarding the risks to human health and environmental quality due to the microbial and toxic components within the wastewater is a serious obstacle for wastewater reuse in agriculture especially in developing countries. As wastewater treatment facilities in most developing countries are non-existent or function insufficiently, farmers in many of these countries use untreated or partially treated wastewater which contains high concentrations of excreta related pathogens and disease agents including bacteria, nematode eggs, viruses, and protozoa These pathogenic organisms have been implicated one of the most important causes of chronic gastroenteric diseases including diarrhoea and outbreaks of acute diseases such as cholera and typhoid. Furthermore, many of these pathogens such as protozoa and helminth eggs have been proved to have significant resistant to conventional biological treatment processes. They are difficult to remove and can survive for a long time in the soil or crop surfaces and as a result they can be transmitted to humans or animals.

Inappropriate management of wastewater irrigation can contribute to serious environmental problems especially in arid and semi-arid zones where wastewater could be the predominant water supply for agriculture (Pescod, 1992, Ayers and Westcot, 1985, WHO, 2006, Simmons et al., 2010). Wastewater irrigation could lead to negative impacts on soil properties and fertility, crop yields, groundwater and surface water quality, and the aquatic ecosystem. The magnitude of the potential impacts will depend on the concentration of the chemicals in the wastewater, their solubility, and inherent toxicity

Most of the existing literature on the safe use of wastewater in agriculture has tended to focus on the associated health risks, provided information from a water quality guidelines perspective or have described public perceptions. There are an increasing number of studies that provide frameworks for evaluating the costs and potential benefits of wastewater reuse projects (Hussain et al., 2001, Morris et al., 2005, Hernández et al., 2006, Winpenny et al., 2010). However, there is still a need for a comprehensive financial and economic analysis that considers all the economic aspects and benefits including intangible costs and benefits (such as health and environmental effects of wastewater reuse project, regulatory costs, public information and education, and value of water) which are generally not included in an economic appraisal of wastewater reuse projects. Furthermore, evaluating the economics of wastewater management options for mitigating environmental risks associated with the chemical constituents in wastewater is a challenge due to many reasons including the fact that many environmental commodities have public good dimensions, do not have market values and may be difficult to quantify in monetary units(Qadir et al., 2015). There is still a need for the implementation of tools or models for assessing environmental risks and risk management approaches which can be used for economic analysis and help decision makers to decide on the available wastewater management options under specific environment, social and economic conditions.

This study seeks to enhance the effective reuse of wastewater for irrigation in arid and semi-arid areas, by developing an integrated approach combining health risk assessment, environmental risk assessment, and a cost-benefit analysis. This study is one of very few research projects that brings the three aspects together. It will provide a tool for decision makers that can be used to estimate the health and environmental risks and assign a value to the costs and benefits of alternative strategies for wastewater reuse in agriculture to optimise the trade-offs between risks to public health and the environment and the preservation of the substantial benefits. The study was based on a case study in Misurata in northern Libya, but will have relevance to a wide range of arid and semi-arid regions with similar agro-ecological features.

1.2 Aim and Objectives

1.2.1 Aim

To develop a novel approach to evaluate the cost-effectiveness of alternative wastewater reuse strategies which incorporates an assessment of both health and environmental risks and the costs and benefits of their management.

1.2.2 Objectives

1. To identify a typology of appropriate representative wastewater management strategies
2. To develop a robust methodology for estimating and summing the health and environmental risks.
3. To develop a robust methodology for calculating life cycle costs and the potential benefits of these strategies.
4. To develop an approach which combines these two methodologies to identify the optimum strategies for wastewater reuse in agriculture context.
5. To validate the approach using a Case Study based in Misurata, Libya.

1.3 Potential Contribution

Given the urgent need to enhance sustainable water resources management in many arid and semi-arid areas and the potential value of wastewater reuse; the lack of any robust systematic analytical approach for comparing various options is a significant barrier. This research, therefore, seeks to make the following contribution:

- Provide a robust methodology that can be used to evaluate environmental risks in agriculture with wastewater reuse and identify appropriate risk reduction strategies.
- Provide a robust methodology to quantify the relative benefits and costs of these wastewater reuse strategies as compared to other water resource management strategies in arid areas with a high dependence on groundwater.

- The most important outcome will be a new evaluation model that can combine the assessment of both health and environmental effects and economic analysis to optimise the management of wastewater.

1.4 Scope of the Study

Due to time limitations this study has been designed to address only the health, environmental and economic issues in developing an evaluation approach for assessing wastewater reuse strategies. Socio-cultural and political aspects were omitted from this study although it is recognised that these aspects are very important factors in the development of effective wastewater reuse strategies; successful implementation of a wastewater reuse strategy is highly dependent on public perception and political constraints. Public perception may be a powerful instrument for the acceptance or rejection of any proposed intervention, particularly the reuse of wastewater in agriculture. Any well-developed reuse scheme could fail due to the public opposition that results from a combination of cultural beliefs, fear, attitudes or lack of knowledge.

Furthermore, effective wastewater reuse strategies need to be facilitated by appropriate policies, legislation, institutional frameworks and regulations at international and national levels. (WHO2006). In many developing countries, including Libya, these frameworks are often lacking. Therefore, to be successful, reuse strategies may need to be implemented in ways which take into account existing legislation, regulations, and national institutions or include specific interventions to modify these.

The implications of benefits and costs associated with wastewater sludge reuse or disposal were not included in the analysis; only those impacts relating to wastewater effluent was included in the approach. It is anticipated that this will underestimate the risks, benefits, and costs associated with all the wastewater reuse options considered in this study. Wastewater sludge from wastewater treatment plants and on-farm systems may be equally or more hazardous to public health and the environment when compared to wastewater. On the other hand they may contain a higher concentration of beneficial nutrients, and therefore the balance of risks and benefits is an important area for further research but lay outside the scope of this study.

1.5 The thesis structure

The thesis consists of the following chapters:

- Chapter 1: gives a general introduction, outlines the aims and objectives and explores the scope and the limitations of this research.

- Chapter 2: gives a comprehensive literature review to exploit the wealth of knowledge and experience in the field of wastewater reuse in agriculture. This is essential as this research seeks to build on existing knowledge and research.
- Chapter 3: presents a review of the current water resource situation and management in Libya. The chapter provides a description of available water resources, the current and future state of water supplies and demands and it also explores the current water resources management practices and their efficiency to overcome the current water crisis in Libya.
- Chapter 4: provides a summary of the research methodology for developing the evaluation model, including the conceptual framework which combines health risk assessment, environmental risk assessment and costs benefits analysis, and data collection methods. In addition, it gives a description of the case study area including the target population, current agricultural activities, and current water and wastewater management practices.
- Chapter 5: provides the approach and the data used for health risk assessment, and the outcome results. Quantitative Microbial Risk Assessment (QMRA) was used for assessing health risks associated with different strategies for wastewater reuse in agriculture.
- Chapter 6: provides the methodology and the data by which potential environmental risks and risk management options are assessed as well as the outcome results of assessing environmental risks associated with different strategies for wastewater reuse in agriculture.
- Chapter 7: describes the model and the data for costs and benefits analysis undertaken with the results of the health and environmental assessment, and the outcome results of costs and benefits analysis to determine the most effective management strategies for wastewater reuse in agriculture.
- Chapter 8: reviews the novel evaluation model developed in this research and outlines the achievements and the limitations of the model, the applicability to be used in other case studies and finally draws a conclusion of the research, and presents recommendation for future research

Chapter 2. Wastewater reuse in agriculture

2.1 Water Scarcity and Wastewater Reuse

Beyond maintaining the essential need for all forms of life and human survival, water is a fundamental resource for sustaining the environment and economic development. In general, water availability and accessibility are the most significant constraints on social-economic development and improved standards of living (Winpenny et al., 2010).

Water scarcity along with inadequate water supply and sanitation and environmental degradation are the major challenges that are facing many regions of the world, especially developing countries. According to some studies, 40% of the world's population today are experiencing water stress (Calzadilla et al., 2011). Currently around 19 countries can be classified as having water scarcity with total renewable water resources less than 500 m^3per capital as is shown in Figure 2-1. By 2025 these countries will be joined by others including South Africa, Pakistan and a large part of China and India (Lazarova and Bahri, 2004, Mancosu et al., 2015). Over the next few decades, water scarcity is expected to increase as a result of a relentless increase in water demands (driven by rapid population growth, growing urban food demand, urbanisation and climate change) (Winpenny et al., 2010).

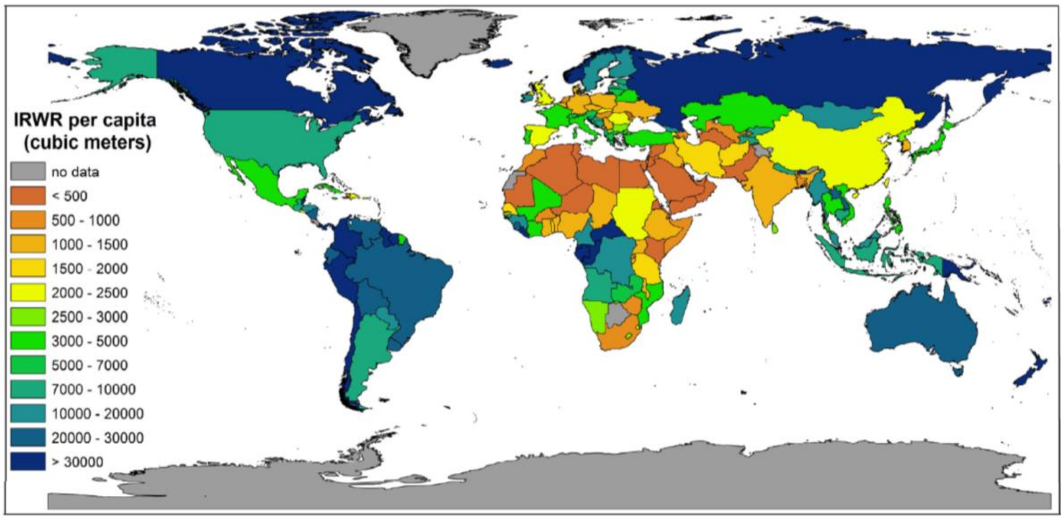


Figure 2-1 World map of internal renewable water resources (IRWR) per country in 2012 data from World Bank Group (Mancosu et al., 2015)

The world's population is expected to grow by 2.3 billion people between 2009 and 2050 (Mancosu et al., 2015), of which 80% percent will be living in developing countries (Calzadilla et al., 2011, Mancosu et al., 2015). It has been estimated that around 1.8 billion people will live in regions with absolute water scarcity with water availability per capita less than 100 m^3, and up to two-thirds of the world's population could experience moderate to high water stress

(Mancosu et al., 2015). The increase in the world's population will also have a significant impact on water supply for food production. It has been estimated that an additional 53% of crops water requirement and additional 38% of land is needed to meet food production goals in 2050 (Mancosu et al., 2015)

Climate change also contributes to increasing water scarcity and according to the fourth assessment report of the Intergovernmental panel on climate change, water availability is expected to decrease by 10-30% as a consequence of climate change. It is estimated global warming of 2°C may lead to a situation where 1 to 2 billion more people will be at high risk of not having access to water for their basic needs (consumption, food, and hygiene) and an additional 400 million could be at risk of hunger (Winpenny et al., 2010)

Meeting the continuous increase in demand for water often comes at a high environmental cost. Available surface water is depleted, many rivers no longer reach the seas, almost half of the world's wetland have disappeared, and overexploiting of groundwater has led to water tables dropping by meters every year and many coastal aquifers have been severely damaged by the intrusion of saline water. All these environmental impacts aggravate scarcity of water and add more pressure on the available fresh water supply (Gourbesville, 2008).

In many countries, especially where water resources are limited, water supplies have been stretched to their limits and the imbalance between water supply and water demand has reached critical levels. In the face of water scarcity, many countries have increasingly realised the importance of water demand management and water conservation for more sustainable supply options. However, in many cases, water conservation strategies may not be enough to close the gap between water supply and demand. In addition, developing water supplies from conventional water resources have increasingly become very difficult due to the prohibitive costs of extraction, infrastructure, and energy; moreover, it can be restricted due to the need for environmental protection and water resource conservation (Winpenny et al., 2010).

Globally, agriculture is by far the largest consumer of water, accounting for approximately 70% of all freshwater withdrawal and up to 90-100 percent in developing countries as shown in Figure 2-2 (Winpenny et al., 2010, Mancosu et al., 2015, Lazarova and Bahri, 2004). With the increase in water demands, irrigated agriculture is facing growing competition from other uses including municipal, industrial and aquatic needs to sustain ecosystems and fisheries. Under these circumstances, it is expected that agricultural water supply will be diverted to more economically and socially valuable purposes such as urban and industrial uses (Raschid-Sally and Jayakody, 2009).

Due to the growing competition between the agricultural and higher-economic-value urban and industrial uses of freshwater supplies, as a result of the increasing demand for water, wastewater has increasingly become the predominant low cost and reliable alternative to conventional water in many countries, especially arid and semi-arid regions. (Kretschmer et al., 2002, Winpenny et al., 2010, Jimenez and Asano, 2008, Scott et al., 2004, Lazarova and Bahri, 2004). For many arid and semi-arid zones reuse of wastewater in agriculture as a substitute for fresh water could contribute considerably to the reduction in water stress and the maintenance of agricultural production (Gourbesville, 2008, Lazarova and Bahri, 2004, Raschid-Sally and Jayakody, 2009). In the Middle East, North and South Africa, northern Mediterranean countries, USA, Australia and parts of China wastewater reuse in agriculture has increasingly become a conmen practice and a key part of water resource management. It can represent between 10 to 40% of the total water supply and about 30 to 70% of water supply for irrigation (Raschid-Sally and Jayakody, 2009).

Although growing water stress can be considered the major driving factor for wastewater reuse, there are also other drivers for the increase in wastewater reuse in agriculture in both developing and developed countries. These include increased urban wastewater flows due to growing urbanisation along with the stringent environmental standards of wastewater and sludge disposal. In addition, there is growing recognition of the resource value of wastewater and its nutrient properties, supported by the Millennium Development Goals for poverty and hunger elimination and ensuring environmental sustainability (Jiménez et al., 2010a, WHO, 2006).

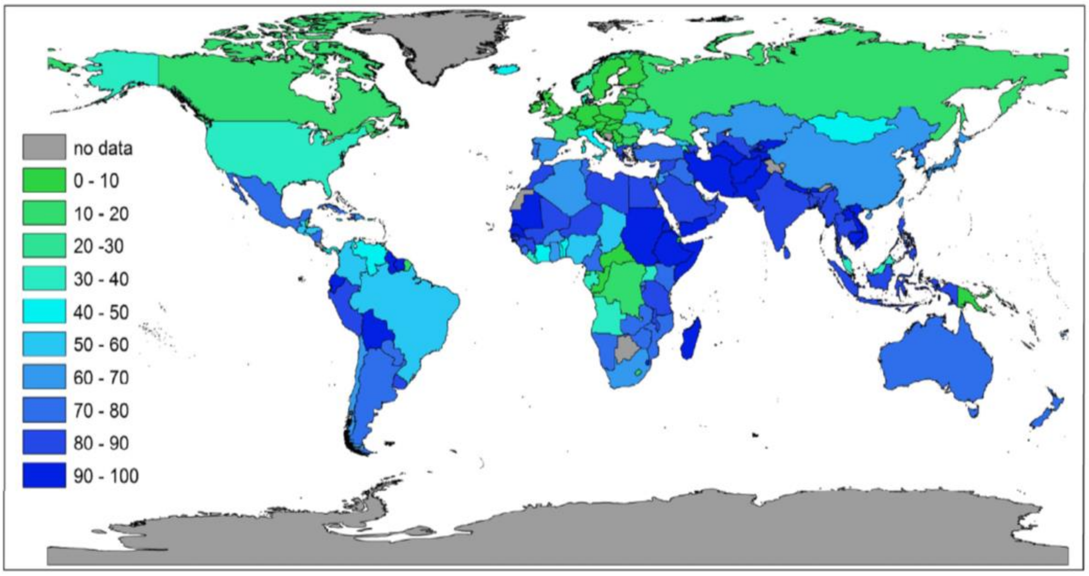


Figure 2-2 Annual freshwater withdrawals in agriculture per country (%), referring to total water withdrawals in 2012 (Mancosu et al, 2015)

2.2 Advantages of Wastewater Reuse in Agriculture

Referring to all drivers for wastewater reuse in agriculture, it is not surprising that agriculture accounts for the largest user of wastewater worldwide (Jiménez et al., 2010a). Wastewater has a wide range of positive impacts that are important considerations for farmers, related communities, and the environment. To a large extent, wastewater can be considered as a reliable source of water and nutrients that are available all year around (Hussain et al., 2002, Qadir and Scott, 2010). Water availability and nutrient properties make it extremely valuable especially in arid and semi-arid climates. It permits higher crop yields, multiple cultivation cycles and allows a wider range of crops to be cultivated (Qadir and Scott, 2010, Jiménez et al., 2010a). Studies carried out in Hubli-Dharwad in India showed that wastewater reuse allowed farmers to cultivate crops in the dry season and sell at prices that were three to five times higher than for monsoon crops (Jiménez et al., 2010a). In Quetta, Pakistani farmers were willing to pay 2.5 times more for access to wastewater in comparison to freshwater access since it allows more crops to be harvested per year (WHO, 2006, Jiménez et al., 2010a). According to studies in Ghana, the significant factor that influences farmers' profits is the ability to produce highly demand crops at the right time so they can be consistently sold at higher prices. This is also reflected in farmers willingness to pay higher fees for water (Cornish and Lawrence, 2001).

Furthermore, the increase in crop productivity and the ability to grow crops close to consumers in urban and peri-urban areas can contribute to improving food availability. In Pakistan, around 26% of vegetables are produced using wastewater irrigation and similarly, in Hanoi, around 80% of vegetables from urban and peri-urban vegetable agriculture is produced using diluted wastewater from the Red River Delta (Qadir et al., 2007). In addition, wastewater reuse can contribute to raising farmer incomes and increase job opportunities, subsequently enhance food security and provide farming communities with more reliable and sustainable livelihoods (WHO, 2006, Jiménez et al., 2010a). For example, a study in Kenya and Ghana shows that using wastewater has a positive effect on the financial capital of urban farmers (Cornish and Kielen, 2004b).

In addition to its reliability, utilizing the fertilizing content of wastewater would also provide more income by reducing the need to purchase fertilizer (WHO, 2006, Jiménez et al., 2010a, Winpenny et al., 2010, Scheierling et al., 2010, Becerra-Castro et al., 2015). In the Guanajuato River basin in Mexico the saving in fertilizer cost as a result of using wastewater was estimated to be worth US$135 per hectare per year. This saving would be a substantial amount of money especially for poor farmers in developing countries (WHO, 2006, Jiménez et al., 2010a). Wastewater even if treated, is rich in organic matter, macronutrients (nitrogen N, phosphorous P, and potassium K) and numerous micronutrients such as iron, zinc manganese and copper more so than any synthetic fertilizer and these components are essential for optimal plant growth. It has been estimated that using 1000 m^3 per hectare of domestic wastewater could contribute 16-62 kg nitrogen, 4-24 kg phosphorus, 2 -96 kg potassium. (Qadir et al., 2007).

Therefore recycling these components could not only reduce the demand for chemical fertilizer and its impact on the environment but also help to improve soil structure and its physical properties (WHO, 2006, Jiménez et al., 2010a, Winpenny et al., 2010, Scheierling et al., 2010). Additionally, wastewater can be an important alternative source of phosphorous to substitute for mining natural limited phosphorous resources (Jiménez et al., 2010a). It could also have an important role in the global carbon cycle and mitigate the accelerated effects of greenhouse gases by increasing soil organic carbon (Qadir and Scott, 2010). Many studies on the long-term effect of wastewater on soil physical properties reveal that wastewater has beneficial effects on soil physical properties and soil organic matter (Qadir and Scott, 2010). A study in India reported that wastewater had increased soil organic carbon by 80% after 15 years of application (Qadir and Scott, 2010).

Wastewater can also contribute to water resource conservation and environmental sustainability (WHO, 2006, Jiménez et al., 2010a). Using wastewater can help to relieve the pressure on water resources as it provides a relatively low-cost water source for the largest water consumption sector worldwide. Utilising wastewater for activities such as agriculture will allow freshwater to be used for more socially and economically valuable uses subsequently achieving a better balance between demand and supply of water in different uses (Hussain et al., 2002, Winpenny et al., 2010)

Safe use of wastewater can contribute to mitigating the effects of wastewater pollution that result from discharging untreated or partially treated water into the aquatic environment particularly in low and middle-income countries (WHO, 2006, Jiménez et al., 2010a, Winpenny et al., 2010, Scheierling et al., 2010). It also offers a low-cost disposal method, as water quality for agricultural use can be achieved easily compared to the quality required for other applications (Hussain et al., 2002, Winpenny et al., 2010).

2.3 Typologies of Wastewater and Wastewater Use

There have been numerous attempts to give broad explanations of wastewater typologies in wastewater management and use in agriculture. Therefore, there are differences in the classification of wastewater typologies that have persisted due to differences in terminologies used by different scholars. The following typologies are commonly used in the literature:

2.3.1 Typologies of Wastewater

The types of wastewater can vary depending on the source and properties of the raw wastewater. In most cases, wastewater used in agriculture can be categorized under four broad typologies, namely gray wastewater, urban wastewater, treated wastewater, and reclaimed wastewater (Mateo-Sagasta et al., 2013).

- **Grey Wastewater** is wastewater originating from domestic wastewater that is not mixed with toilet waste. Grey water is the water used for household chores such as water from laundry tubs, washing machines, washbasins, showers, and bathtubs.
- **Urban Wastewater** is a broad wastewater topology which includes effluent wastewater from gray water, black water (excreta, urine, and associated sludge), commercial effluents (from commercial establishments and institutions and may include industrial effluents), and stormwater and other urban runoffs.
- **Treated wastewater** is wastewater that has been processed through one or more physical, biological and chemical processes to produce a certain range of effluent qualities.
- **Reclaimed wastewater** is the official use of treated wastewater under controlled conditions for beneficial purposes, such as irrigation.

2.3.2 Typologies of Wastewater Use

There is a different categorization of wastewater use and the following typologies of wastewater use are the most relevant with regards to application in agriculture (WHO, 2006, Jiménez et al., 2010a, Mateo-Sagasta et al., 2013):

- **Direct use of treated wastewater**. Under such category, wastewater is treated (or reclaimed) through a wastewater treatment system and transported to point of use (e.g. irrigation fields) without coming into contact with groundwater and surface water bodies.
- **Direct use of untreated wastewater** is the use of raw wastewater from a sewage outlet, directly disposed of on land where it is used for crop production.
- **Indirect use of untreated wastewater** entails abstracting diluted wastewater (or polluted water from streams receiving wastewater) and applying it for irrigation purposes. It is common practice in urban centres with limited treatment plants and the farmers utilizing diluted wastewater have little or no knowledge about the water quality challenge
- **Planned wastewater uses** which are described as the controlled and conscious utilization of wastewater either undiluted (direct) or diluted (indirect). Most of the indirect use usually is unplanned.

In the topology of planned reuse of wastewater are two subcategories, which include.

- **Restricted irrigation** is the controlled use of wastewater to grow crops that are not eaten raw by humans
- **Unrestricted irrigation** is the controlled use of treated wastewater to grow crops that are normally eaten raw

2.4 Wastewater Reuse in Agriculture around the World

Currently, reuse of wastewater in urban and peri-urban agriculture is already a common practice worldwide (Winpenny et al., 2010, Jiménez et al., 2010a). It is estimated that 6-20 million hectares are irrigated with wastewater in 3 out of 4 cities in developing countries (Wichelns et al., 2015). Figure 2-3 shows countries with recorded use of wastewater in agriculture.

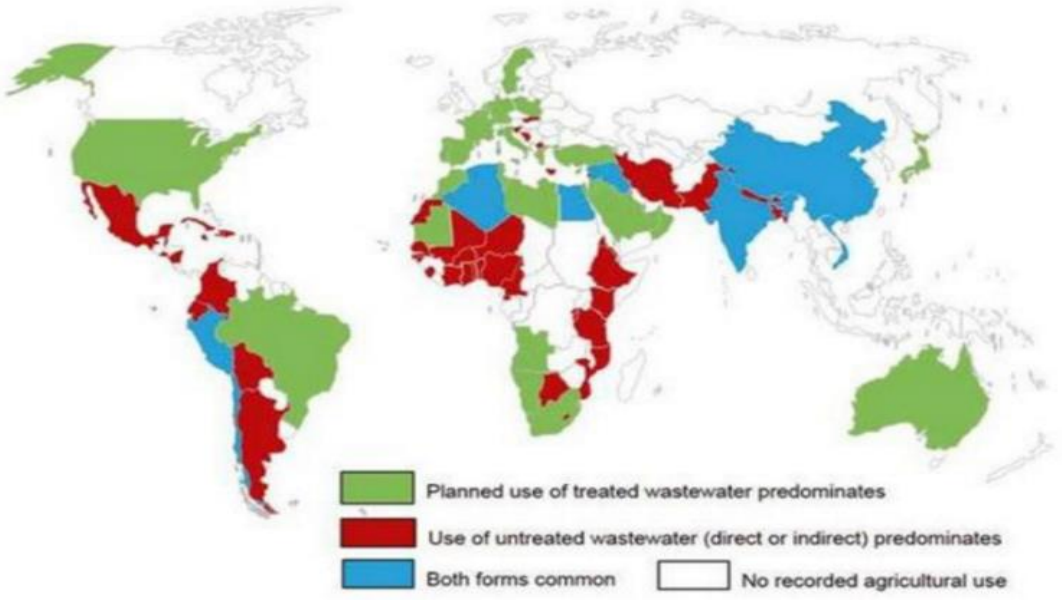


Figure 2-3 Countries with recorded use of wastewater in agriculture (Wichelns et al, 2015)

Data on current wastewater (both treated and untreated) use in agriculture worldwide is mostly based on rough estimates. Figure 2-4 illustrated the 20 countries with the largest recorded agricultural areas irrigated with wastewater, both untreated and treated.

Although direct use of untreated wastewater is banned in most countries, the practice still takes place in urban and peri- urban areas in many developing countries. Most of the direct use of untreated wastewater occur in low-income countries where access to an alternative water source is limited due to scarcity, quality issues (e.g. saline groundwater) or unaffordable costs of accessing (e.g. pumping cost). There are many examples of the direct use of untreated wastewater from South Asia, Latin America and Africa (Wichelns et al., 2015). In many cities in Pakistan, farmers use untreated wastewater because groundwater and treated wastewater are too saline to use (Wichelns et al., 2015). It has been estimated that in Pakistan around 32,500 ha mostly for vegetable crops are irrigated with wastewater, of which only a negligible proportion are treated (Van der Hoek, 2004, Jiménez et al., 2010a). In Karnataka in India farmers use wastewater from open or underground sewers for irrigation as they cannot afford the cost of groundwater access. There are other cases from Haroonabad and Faisalabad in Pakistan and Hyderabad in India where untreated wastewater is the only water source for irrigation (Wichelns et al., 2015, Cornish and Kielen, 2004b). In Chile and Argentina, the areas irrigated with untreated wastewater are similar to the areas irrigated with treated wastewater (Jimenez and Asano, 2008, Sato et al., 2013) In Mexico where there are probably some of the oldest and largest wastewater reuse schemes in the world, untreated wastewater from Mexico City is transported to the Mezquital valley to feed an extensive network of irrigation canals that services around 90,000 ha of various crops such as cereals, vegetables, and fodder.(Van der Hoek, 2004, Sato et al., 2013). Irrigation with untreated wastewater is a very common practice in many cities in Africa such as Accra, Tamale, and Kumasi in Ghana, and Maili Saba and Nairobi in Kenya (Keraita and Drechsel, 2004, Cornish and Kielen, 2004a).

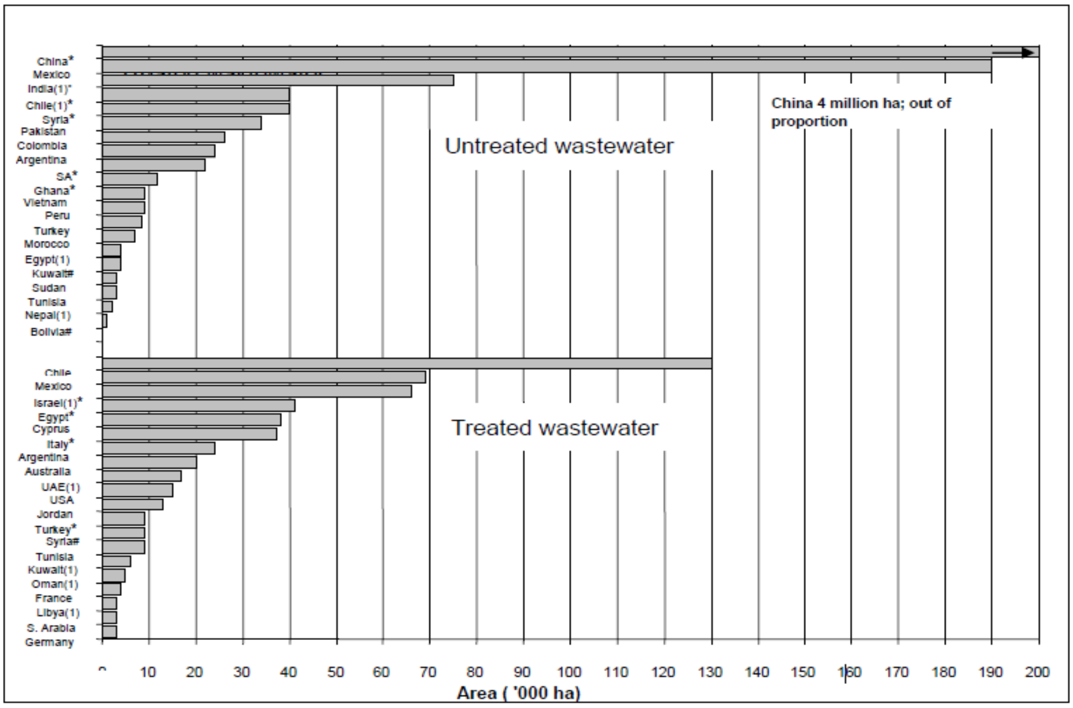


Figure 2-4 **Countries with largest areas irrigated by untreated and treated wastewater (Jimenez and Asano, 2008)**

*Data uncertain; (1) Area probably underestimated; + Practice reported (including forestry), but data missing

The most extensive type of wastewater reuse is indirect use of untreated wastewater which occurs more frequently in both low and middle-income countries where there is little or no capacity for collecting and treating wastewater. As a consequence, untreated or partially treated wastewater is discharged to freshwater bodies (e.g. streams, rivers) and becomes diluted and used (mostly unintentionally) by downstream farmers (Wichelns et al., 2015, Jiménez et al., 2010a). Indirect use of untreated wastewater has been reported in many countries in South Asia (India, China, and Vietnam), West Africa, the Middle East (Syria, Egypt, Jordan and Lebanon), and Latin America (Brazil, Argentina, Colombia and Mexico) (Wichelns et al., 2015, Jiménez et al., 2010a). For example, in Beijing in China 50% of the wastewater generated in the city is discharged to water bodies without treatment and is subsequently used by downstream farmers. In Hanoi in Vietnam about 80% of vegetable crops are produced in urban and peri-urban areas using diluted wastewater (Jiménez et al., 2010a). Also, In major cities in West Africa between 50 and 90% of urban and peri-urban vegetables are irrigated with polluted water (Jiménez et al., 2010a).

In the Middle East due to the lack of wastewater treatment facilities with sufficient capacity to accommodate increased volumes of wastewater resulting from growing urban populations, most of the wastewater collected from the sewage system is discharged to rivers or wadis either untreated or insufficiently treated and used by the downstream farmers. In Syria, it is estimated that around 40,000 ha are indirectly irrigated with untreated wastewater due to the lack of affordable or available alternative water resources (Jimenez and Asano, 2008, Sato et al., 2013). In Egypt, it was estimated that 2 to 3 billion m^3 of raw wastewater was discharged annually into the Nile River and used in the delta region for unrestricted irrigation. Wastewater enters the Nile irrigation system by two different pathways, firstly when raw wastewater is discharged into the agricultural drainage system and secondly when it is discharged into freshwater canals (Guardiola-Claramonte et al., 2012).

Planned use of treated (or reclaimed) wastewater mostly occurs in arid and semi-arid regions in high-income countries including the United States of America, Australia, and Southern Europe countries. In the US, a considerable volume of the total reclaimed wastewater that is available is reused for agricultural and landscape purposes with California and Florida accounting for the vast majority of wastewater reuse for agricultural irrigation. It was estimated that about 46% and 44% of reclaimed wastewater is reused for irrigation in both states respectively. In California, wastewater irrigation dates as back as far as 1890 and 1912 for agricultural and landscape purposes respectively. Currently, wastewater reuse is an integrated part of a water management plan in California with the predominant use being agricultural applications. Around 20 different types of crops are grown using reclaimed wastewater including raw vegetables, cereals, strawberries and non-food crops (Hamilton et al., 2007, Jimenez and Asano, 2008).

Since the mid-1990s there has been a steady increase in the quantity of reclaimed wastewater reuse in Australia for horticulture and agriculture. The wastewater reuse mostly takes place in rural areas away from the coast as these are the areas that have limited rainfall and are highly suited for agriculture. It is estimated that about 103 GL/year of reclaimed water is used by the agricultural sector (Seshadri et al., 2015) and one of the largest reuse projects is the Virginia

Pipeline Scheme in South Australia for horticulture which provides 20 GL/ year of reclaimed wastewater to 230 horticulturalists (Hamilton et al., 2005).

In Southern European countries, agricultural irrigation accounts for 44% of the wastewater reuse projects (Sato et al., 2013). For example, in Spain, there are more than 150 reclaimed wastewater reuse projects around the country mostly for agricultural reuse (71%) but also for environmental services (17%)(Guardiola-Claramonte et al., 2012, Sato et al., 2013). France has around 30 wastewater reuse projects for agricultural purposes where more than 3000 ha is irrigated with treated wastewater. The treated wastewater is used for various irrigation purposes, including growing crops (vegetables, orchards, maize, cereals), tree plantations and forests, golf courses, and public gardens (Hamilton et al., 2007). Wastewater reuse is the second alternative water resource in Cyprus where around 25 million m^3 of treated wastewater is recycled, mostly for agricultural activities and it is estimated that 38,200 ha are irrigated with treated wastewater (Jimenez and Asano, 2008). In Italy, agriculture is the main use of wastewater with around 28,285 ha being covered by wastewater irrigation.(Jimenez and Asano, 2008). Israel is a world leader in treated wastewater reuse for agricultural irrigation (According to the Israeli Water Authority (2014) and it is estimated that in 2012 treated wastewater made up 39.6% of the total agricultural water consumption which almost equal to the fresh water proportion (Schacht et al., 2016).

Currently, in the Middle East and North African countries irrigation with treated wastewater has increasingly become a common practice. For example, in Arabic Gulf countries 44% of treated wastewater is reused for agriculture (Jimenez and Asano, 2008). In Kuwait reuse of wastewater for agriculture accounts for around 35% of the total water extraction (Winpenny et al., 2010). Tunisia has been recognised as a leader in North Africa in terms of wastewater reclamation and uses about 78% of the collected wastewater which has been treated to secondary biological standard which represents approximately 5% of total available water in the country (Carr et al., 2004, Winpenny et al., 2010, Qadir et al., 2010) Around 30 to 43% of this treated water is reused for irrigation purposes including landscape irrigation, fodder and industrial crop production, grain cultivation and to irrigate fruit trees such as vineyards and citrus (Winpenny et al., 2010). In Jordan which is one of the most drought stressed countries in the Middle East, to meet the increasing water demand, more than 70 million m^3 of reclaimed wastewater is used directly or indirectly, contributing around 10% of the total national water supply and most of it is used for agriculture (Scheierling et al., 2010).

2.5 Risks from wastewater reuse for irrigation in agriculture

2.5.1 Microbial risks

Using wastewater in agriculture may pose substantial risks to public health, food safety and environmental quality (Scott et al., 2004, Scheierling et al., 2010). As wastewater treatment facilities in most developing countries are non-existent or function insufficiently, farmers in many of these countries use untreated or partially treated wastewater. Untreated or partially treated wastewater contains high concentrations of excreta–related pathogens and disease agents including bacteria, nematode eggs, viruses and protozoa (WHO, 2006).These pathogenic organisms have been implicated as the most important cause of chronic gastroenteric diseases including diarrhoea and outbreaks of acute diseases such as cholera in Jerusalem and Dakar and typhoid in Santiago. (Owusu et al., 2012, Scott et al., 2004). Hussain et al. (2002) Reported that in Pakistan, farmers who use wastewater have a higher rate of diarrhoeal disease incidence than farmers using groundwater.

Many of these pathogens such as the protozoa and helminth eggs prove to have significant resistant to conventional biological treatment processes. Therefore they are difficult to remove and can survive for a long time in soil or on crop surfaces and may consequently be transmitted to humans or animals (WHO, 2006). A study conducted in Dakar in Senegal indicated that farmers who mainly use untreated wastewater are more likely to have a higher rate of intestinal parasites compared to those who use diluted wastewater (Owusu et al., 2012). Skin diseases are also another problem associated with direct exposure to wastewater (Bos et al., 2010, Owusu et al., 2012). In Cambodia and Vietnam, skin disease such as dermatitis has been attributed to contact with untreated wastewater. Problems such as blistering and itching in hands and feet have also been reported by rice farmer in India, and urban vegetable farms in Ghana (Bos et al., 2010).

The health risks associated with wastewater are not limited to agricultural workers only but can be observed in workers families and nearby communities through exposure to wastewater and the consumption of produce grown using wastewater especially when eaten uncooked and also produce handlers (Bos et al., 2010). For example, it has been reported that in Sub-Saharan Africa irrigating urban vegetables with highly microbial contaminated wastewater increased the related health risks to both farmer and consumer (Owusu et al., 2012). Also, evidence provided by (WHO, 2006) suggest that both farmers' families and the consumers of wastewater-irrigated crops more frequently contract helminth infections such as Ascaris and hookworm. In Haroonabad in Pakistan, it has been reported that the prevalence of hookworms infections for farmers can get as high as 80% as a result of using untreated wastewater (Bos et al., 2010).

2.5.2 Chemical risks

In addition to the microbiological risks, the practice of wastewater reuse can pose a range of other potential risks to human health and environmental quality as a result of a great variety of toxic organic, and inorganic chemicals that are present in the wastewater. (Qadir et al., 2010). In general, the key issues relating to the chemical constituents of wastewater and its subsequent use in agriculture are excessive levels of salt, heavy metals, excessive nutrients and toxic organic and inorganic compounds:

2.5.2.1 Excessive levels of Salt

Wastewater usually has a higher concentration of total dissolved solids and major ions and higher electrical conductivity than fresh water especially in regions with a hot climate where there is a long dry season and a high rate of evaporation. These dissolved solids and ions originate from many sources such as detergents and washing material, chemicals used during the treatment process and other sources (Toze, 2006a, Qadir and Scott, 2010, Muyen et al., 2011, Becerra-Castro et al., 2015). Salinity levels in wastewater vary and it can range from slightly saline (with electric conductivity EC 0.75 dS/m) to saline water (EC >3 dS/m) while sodicity (SAR) levels were between 1.9 and 20.8 (Qadir and Scott, 2010).

If excessive salt is not removed, long-term use of wastewater could lead to salt accumulation in the soil layers which has been observed to be more pronounced in the topsoil as a result of evaporation. It can also cause elevated concentrations of exchangeable sodium cations (Na^+) and a higher exchangeable sodium percentage (ESP) (Qadir and Scott, 2010, García and Hernández, 1996, Rietz and Haynes, 2003, Hamilton et al., 2005). For example, a study conducted in Jordan shows that wastewater reuse increased soil salinity two to three times compare to a control site (Al-Zu'bi, 2007). Also long-term wastewater reuse (up to 80 years) in the Valley of Mezquital in Mexico led to increasing soil salinization, and especially Na saturation (Friedel et al., 2000). Another example from arid and semi-arid Western USA shows that site irrigated with recycled wastewater exhibited a 187% higher EC and 481% higher sodium adsorption ratio (SAR) compared with sites irrigated with fresh water (Qian and Mecham, 2005). It has been estimated that an annual application of 1000 mm of wastewater with 500 mg/l of total dissolved solids (TDS) may lead to an additional 5t/h/year of salt in the soil unless it is properly drained (Muyen et al., 2011). Increased soil salinity has significant effects on the hydraulic properties, degradation of soil structure and can result in a decrease in soil productivity and crop yields.

Excess levels of specific ions including sodium (Na), boron (B), and chloride (CL) could also affect plant growth through adverse osmotic effects, phytotoxicity or plants nutrient deficiency (Qadir and Scott, 2010). A study conducted in 1993 showed that use of saline wastewater (

>2000 mg/l TDS) led to a decrease in Maize and Sorghum crop yield (Muyen et al., 2011). Furthermore, it could also contribute to groundwater pollution particularly in areas with shallow groundwater (Qadir and Scott, 2010, García and Hernández, 1996, Rietz and Haynes, 2003, Hamilton et al., 2005).

2.5.2.2 Metalloids and heavy metals

Typically, municipal wastewater has lower concentrations of inorganic chemicals compared to industrial effluents, and usually, conventional treatment processes are capable of significantly reducing their concentration and most will accumulate in the sludge (bio-solids) (Hamilton et al., 2007, Chen et al., 2013a, Toze, 2006a).

In general, the risk from inorganic chemicals particularly heavy metals found in wastewater is higher when industrial wastewater is mixed with municipal wastewater, a common practice in developing countries where industrialisation is accelerating and mixed wastewater is used untreated or partially treated (WHO, 2006). Where industrial effluent is used, it has been reported that heavy metal concentrations in plant tissues were higher than permissible limits even when the wastewater and soil samples comply with established safe standards (Chen et al., 2013b, Khan et al., 2008). Edible crops and fodder irrigated using wastewater could act as a transmission route for heavy metals in the human food chain (Scott et al., 2004). Evidence based on a survey study in India detected high levels of heavy metal transmission from wastewater to cow's milk via wastewater irrigated grass which was fed to cattle. The milk samples were severely contaminated by cadmium (Cd) and lead (Pb) with concentrations ranging from 1.2 to 40 times above the permitted level (Scott et al., 2004, Qadir and Scott, 2010).

Based on many studies in Southeast Asian countries such as Pakistan, India, and China, where industrial effluent together with sewage (diluted or untreated) is widely used for irrigation, it has been found that cadmium followed by lead were the major metals which pose a risk to health (Khan et al., 2013, Tiwari et al., 2011, Khan et al., 2008, Singh et al., 2010, Lu et al., 2014, Verma et al., 2015)

Generally, it has been reported that cadmium is the major relevant heavy metal which presents a risk to human health. It has high mobility and an ability to bioaccumulate in crops at very low concentrations that are not phytotoxic but could pose health risks to human (Hamilton et al., 2007, WHO, 2006, Chen et al., 2013c, Khan et al., 2013). Many metals such as manganese (Mn), Zinc (Zn), and Copper (Cu) pose little hazard to humans through contamination of the food chain due to the fact that they have significant phytotoxic effects in low concentrations which are not toxic to humans and as a result the plant will die before it presents a rik to health (Simmons et al., 2010).

Uncontrolled inputs of metal and metalloids to the soil are undesirable since they are extremely difficult to remove once they have accumulated and eventually may be absorbed by the plants or transported from the soil to water bodies, thereby contaminating the water supplies (Simmons et al., 2010).

2.5.2.3 Excessive Nutrients

Wastewater commonly contains high concentrations of nutrients in the form of nitrogen, phosphorus and potassium. Nutrient concentration will vary significantly, depending on whether untreated, diluted or treated wastewater is used. Table 2-1 provides an overview of typical nutrient concentration ranges in untreated wastewater and in treated effluent from secondary and advanced tertiary processes.

Table 2-1: Typical nutrient concentration ranges in untreated and treated effluent

Constituent (mg/l)	**Untreated Wastewater**	**Conventional activated sludge** [a]	**Activated sludge with BNR** [b]	**Activated sludge with BNR, microfiltration, and Reverse osmosis** [c]
Total nitrogen	35-60	15-35	3-8	≤1
Ammonia –N	20-45	1-10	1-3	≤0.1
NO3–N	0–trace	10-30	2-8	≤ 1
Total Phosphorus	4-15	4-10	1-2	≤0.5

a. Secondary treatment: activated sludge including a nitrification step
b. Tertiary treatment: activated sludge and biological nutrient removal of nitrogen and phosphorus
c. Tertiary treatment: activated sludge and biological nutrient removal combined with advanced treatment

Sources: (Sperling and de Lemos Chernicharo, 2005)and (Carey and Migliaccio, 2009)

Although the nutrient supply capacity is considered to be the main driver for wastewater reuse in agriculture, nutrient concentrations in wastewater can reach levels which are excessive. This could result in possible negative effects of nutrients oversupplying especially nitrogen and phosphorus. Oversupply of nitrogen through wastewater reuse could lead to excessive vegetative growth, delay in maturity and reduced crop size and quality which will result in low economic yield (WHO, 2006, Hamilton et al., 2005, Qadir and Scott, 2010, Chen et al., 2013a). Nitrate leaching is another concern associated with excessive nitrogen in wastewater which may lead to contamination of groundwater causing health problems including methemoglobinemia in neonates (WHO, 2006, Hamilton et al., 2005, da Fonseca et al., 2007, Gwenzi and Munondo, 2008, Knobeloch et al., 2000, Candela et al., 2007). Furthermore, excessive nitrogen and phosphorous in wastewater may impact soil microbial communities, in particular, the microbial activities associated with cycling of these elements (Becerra-Castro et al., 2015). The excess of nutrients can disturb the autochthonous soil microbial communities, for example, the accumulation of inorganic-N (NO_3-N and NH_4-N) in soils could affect the microbial catabolic activity, especially the biodegradation of recalcitrant carbon compounds that are present in soil (DeForest et al., 2004, Ramirez et al., 2012). Both nitrogen in form of NO_3-N and P can reach surface water via drainage systems or soil erosion and cause eutrophication or toxicity in other habitats (Hamilton et al., 2005, WHO, 2006, Wu, 1999).

2.5.2.4 Toxic organic compounds and emerging contaminants

Wastewater contains a wide variety of toxic organic compounds including priority organic pollutants such as pesticides (DDT, 2,4-D, Aldrin), industrial compounds (phthalates PCBs, non–ionic detergents), disinfection by-products, synthetic and natural hormones, pharmaceuticals and personal care products (PPCPs) (WHO, 2006, Onesios et al., 2009, Bolong et al., 2009, Muñoz et al., 2009, Cizmas et al., 2015). Many of these can be difficult to detect due to the lack of suitable analysis techniques that are able to directly detect them in low concentrations, Furthermore, they vary considerably in their form and their mechanism of actions which makes the identification and evaluation of these compounds a unique challenge (Bolong et al., 2009). These toxic pollutants may have carcinogenic, teratogenic and mutagenic effects and many of them are Endocrine Disrupters Chemicals (EDCs) which means that they may interfere with hormone functions in animals and humans. (WHO, 2006, Qadir and Scott, 2010, Bolong et al., 2009, Cizmas et al., 2015, Wu et al., 2015). Although direct evidence of negative human health effects are still being debated (Bolong et al., 2009, WHO, 2006, Toze, 2006a, Onesios et al., 2009, Bergman et al., 2013), relationships have been identified between endocrine disruptors and increased incidences of endocrine-related cancers such as breast, ovarian, prostate, testicular and thyroid cancer (Cizmas et al., 2015, Bergman et al., 2013). Abnormalities, altered immune function and population disruption due to exposure to these pollutants have also been observed in birds, reptiles, mammals, amphibians and invertebrates (WHO, 2006, Colborn et al., 1993, Bergman et al., 2013).

Many EDCs and PPCPs could persist in the environment and may accumulate in irrigated soils or eventually reach surface water or groundwater, leading to human exposure through drinking water (WHO, 2006, Chen et al., 2013a, Chen et al., 2011). From the data available in the literature, soil systems are better equipped than water courses for the degradation of many of these compounds, with mechanisms including microbial degradation or adsorption by soil organic matter (Qadir and Scott, 2010, Chen et al., 2011, Dalkmann et al., 2014, Qin et al., 2015). However, it is still possible that some of them such as PPCPS may be taken up by crops or transferred to the edible surface of crops as a result of irrigation with wastewater or soil that remains on the surface of crops after harvesting (WHO, 2006, Wu et al., 2015). Most of the studies on plant uptake of PPCPs were conducted in greenhouses or in the laboratory and data on the accumulation of these chemicals in crops irrigated with wastewater under realistic conditions is limited (Wu et al., 2015). However, research findings reported to date would suggest that the potential for these substances to enter edible parts of crops was low under normal field conditions (Wu et al., 2015, Prosser and Sibley, 2015). The literature also suggests that their effects on the quality of crops could be negligible (Chen et al., 2011, Wu et al., 2015). The major concerns related to PPCPs are the potential development of antibiotic resistance in soil and water microorganisms as a result of discharging antibiotics into the environment (Toze, 2006a, Chen et al., 2011, Cizmas et al., 2015). Currently, considerable uncertainty exists regarding the potential risks of PPCPs and their transformation products to agricultural and environmental health. (Qin et al., 2015, Bergman et al., 2013). Although the presence of these substances in the environment and their potential ecological effects are generally alarming, their concentration in water sources and other environmental receptors to date are very low (Qadir and Scott, 2010), in addition, many of these chemicals have potential short environmental half-lives (Toze, 2006a, Chen et al., 2011).

2.6 Safe use of wastewater in agriculture

2.6.1 Assessing and Managing Microbial Risks

As it has been mentioned that wastewater reuse in agriculture poses many risks to human health and environment quality. Certainly, the most important health concern from the use of wastewater in agriculture are the health risks associated with pathogen exposure through contact with wastewater (farmers and their families, field workers, and nearby communities) or consumption of wastewater-irrigated products (Bos et al., 2010). In a place where wastewater is reused in agriculture without adequate treatment the primary pathogens that are likely to cause diseases are excreta-related pathogens (bacteria, viruses, protozoa, and helminths), vector-borne pathogens and skin irritants ((Bos et al., 2010, WHO, 2006). Many of these pathogens are capable of surviving in the environment (water, soil, and crops) for long enough to be transmitted to humans (WHO, 2006). Table 2-2 provides an example of the different pathogenic hazards associated with wastewater reuse in agriculture and their exposure routs.

Not all the pathogens transmitted to humans will cause illness and the burdens of diseases depend on the type of pathogen and the exposure routes (Bos et al., 2010). It also varies from region to region and over the time depending on the level of sanitation and hygiene and type of wastewater used in agriculture (Bos et al., 2010); Table 2-3 shows an example of the mortality rates and morbidity (measured in disability adjusted life years DALYS) for some diseases that are relevant to wastewater reuse in agriculture; most of these diseases occur in children in low income countries. Many factors affect the ability of pathogens to cause illness including their persistence in the environment, minimum infective dose, ability to induce human immunity and latency periods. Pathogens with long persistence, the minimum infective does, long latency such as intestinal helminths have a high probability of causing infection (Bos et al., 2010).

Table 2-2 The different types of pathogen associated with wastewater reuse in agriculture (adapted from WHO, 2006)

Pathogen	**Exposure route**	**Relative importance**
Excreta –related pathogens:		
Bacteria: E. coli, salmonella spp, vibrio cholera, shigella spp	Contact, consumption	Low -high
Helminthes:		
• Soil-transmitted :Ascaris, hookworms, Taenia spp.	Contact, consumption	Low -high
• Schistosoma spp.	contact	Nil-high
Protozoa:		
Giardia intestinalis, Cryptosporidium, Entamoeba spp.	Contact, consumption	Low-medium
Viruses:		
hepatitis A virus, hepatitis E virus, adenovirus, rotavirus, norovirus)	Contact, consumption	Low-high
Skin irritants and infections	Contact	Medium -high
Vector-borne pathogens:		
Filaria spp., Japanese encephalitis virus, *Plasmodium* spp.)	Vector contact	Nil-high

To protect public health and avoid any excessive burden of disease for farmers, field workers, consumers and nearby communities it is essential to assess and manage any microbial risks associated with the reuse of wastewater in agriculture. This can be achieved by implementing practical guidelines that offer feasible risk management solutions and facilitates the beneficial reuse of the valuable resource (Carr et al., 2004).

Table 2-3 Global mortality and DALYs due to some diseases of relevance to wastewater use in agriculture (Adapted from WHO, 2006)

Disease	Mortality (deaths/year)	Burden of disease (DALYs)	Comments
Diarrhoea	1,682,000	57,966,000	99.7% of deaths occur in developing countries; 90% of deaths occur in children; 94% can be attributed to environmental factors.
Typhoid	600,000	N/A	Estimated 16,000,000 cases per year.
Ascariasis	3000	1,817,000	Estimated 1.45 billion infections, of which 350 million suffer adverse health effects.
Hookworm disease	3000	59,000	Estimated 1.3 billion infections, of which 150 million suffer adverse health effects.
Lymphatic filariasis	0	3,791,000	Mosquito vectors of filariasis (Culex spp.) breed in contaminated water. Does not cause death but leads to severe disability.
Hepatitis A	N/A	N/A	Estimated 1.4 million cases per year worldwide. Serological evidence of prior infection ranges from 15% to nearly 100%.

N/A: Not available

2.6.1.1 Microbial Guidelines of safe wastewater reuse in agriculture

Concern about the risks to public health is a serious issue for wastewater reuse in agriculture. International guidelines for safe use of wastewater in agriculture and water quality standards exist and have been applied with different degrees of success (Van der Hoek, 2004). Most of these guidelines set huge emphasis on the microbiological quality (in particular faecal coliforms and helminth eggs concentrations) of recycled wastewater (Carr et al., 2004). Many countries in the world base their regulations and rules on a combination of two different approaches, firstly based on potential risks and adopted by California and the United States Environmental Protection Agency USEPA guidelines (Scheierling et al., 2010) and secondly, based on actual risks from epidemiological evidence and adopted by the 1989 guidelines of the World Health Organization WHO (see BOX 2-1)

BOX 2-1 Actual and potential health risks in wastewater:

An actual risk to public health occurs as a result of wastewater when all of the four following conditions are satisfied:

(1) Either an infective dose of the pathogen reaches the wastewater-irrigated field or the pathogen multiples in the field to form an infective dose

(2) The infective dose reaches a human host

(3) The host becomes infected

(4) The infection causes disease or further transmission.

Actual risks can thus only be determined from epidemiological studies. If conditions 1−3 are satisfied but not condition 4, then the risk is only a potential risk.

Source: quoted from (Scheierling et al., 2010)

The Californian guideline is the first microbial effluent standard and for many years was the only legally valid reference for wastewater reuse (Fattal et al., 2004, Winpenny et al., 2010). These guidelines set very strict standards including a concentration of 2.2 faecal coliforms per 100ml (Mara et al., 2007). In 1992, a new set of guidelines were developed by the USAPA together with the United States Agency for International Development (USAID) mainly for use in the United States. These guidelines are even stricter than the Californian standards and call for zero detectable microbial indicator species/ml (e.g. zero FC per 100ml) regardless of the technical feasibility and cost-effectiveness of removal technologies (Fattal et al., 2004). This “no risk” approach needs rigorous treatment and numerous and expensive engineering requirements (Hussain et al., 2002, Fattal et al., 2004). Therefore, these guidelines may be considered as unachievable in many parts of the world especially in developing countries (Hussain et al., 2002, Fattal et al., 2004). Moreover, applying these guidelines would result in the removal of the nutrient components from reclaimed water that are beneficial for crops since they require tertiary or (advanced treatment) such as (membrane filtration).

Based on epidemiological studies on public health risks associated with wastewater exposure reviewed by three independent teams of epidemiologists, social scientists and sanitary engineers, in 1989 WHO published guidelines for the reuse of wastewater in agriculture and aquaculture (Hussain et al., 2002, Fattal et al., 2004). The rationale behind these guidelines was to prevent the transmission of wastewater related diseases by developing effluent quality standards,such as a limit of 1000 faecal coliforms/100ml and less than one helminth egg/lfor unrestricted use (Mara et al., 2007). The guidelines also took into consideration risk management measures such as wastewater application measures, crop selection and human exposure control (Drechsel et al., 2002). These recommendations aimed to help the engineer and the planner in the choice of wastewater management options and treatment technology (Drechsel et al., 2002). The 1989 guidelines have been widely accepted by many international agencies and organization including the United Nations Environmental Programme, the United Nations Development Programme, and the Food and Agriculture Organisation (Fattal et al., 2004).

Although these guidelines have been influential and have been adopted by many developed and developing countries (Fattal et al., 2004, WHO, 2006), the application of these guidelines has been difficult to implement in many developing countries particularly low-income countries for a number of reasons. For example, the guidelines require an adequate level of biological treatment, but many developing countries suffer from the lack of sanitation facilities and sewerage while wastewater treatment facilities are almost non-existent (Drechsel et al., 2002). In addition, in most of the low-income countries such as Sub-Saharan countries untreated or diluted wastewater reuse is usually unplanned and unregulated (Scott et al., 2004). Given that wastewater in urban and peri-urban agriculture has an important role to play in food supply and contributes to the sustainability of livelihoods in these countries many authorities find the responsibility of regulating this practice is a burden. In the absence of governmental resources for wastewater collection and treatment infrastructure, they tend to turn a blind eye (Scott et al., 2004, Van der Hoek, 2004).

In order to achieve the balance between safeguarding public health and ensuring the beneficial use of the scarce resources, guidelines should consider that in many developing countries where wastewater is used for agriculture; wastewater treatment may not be a feasible option (Carr et al., 2004, Bos et al., 2010). Therefore, instead of focusing on the wastewater effluent quality at its end use point, WHO in collaboration with FAO, has updated the 1989 guideline for the use of wastewater in agriculture to be more practical and provide feasible risk management strategies for safe application of wastewater, particularly in developing countries. The new risk-based guidelines provide tools and approaches to define realistic health-based targets and to assess and manage the risks at different barriers from wastewater generation to the consumption of wastewater irrigated produce in order to achieve these targets (WHO, 2006, Drechsel et al., 2008, Bos et al., 2010). It would give national authorities more flexibility to adjust the guidelines and develop their own procedures and regulations based on the local socio-economic and environmental conditions (Bos et al., 2010, Scheierling et al., 2010).

2.6.1.2 Application of the Third Edition of the WHO Guideline in Wastewater Reuse for Agriculture

The third edition of the WHO Guidelines for the safe use of wastewater, excreta, and greywater in agriculture has radical changes from the second edition. The principle differences from the second edition can be summarised as follows (Mara and Bos, 2010):

- The use of a risk-based approach to estimate the required pathogen (bacteria, viruses, and protozoa) reduction.
- In order to protect the health of farmers, field workers and another groups who may be exposed to wastewater, the required pathogen reduction can be achieved via wastewater treatment only (restricted)
- In order to protect the consumers of wastewater irrigated crops, the required pathogen reduction can be achieved by a combination of wastewater treatment and other post-treatment and health protection measures

The new guidelines represent a progressively integrated risk assessment and management approach that follows the Stockholm framework shown in Figure 2-5 to achieve health- based targets (WHO, 2006). The guidelines consider two main groups of wastewater related diseases associated with the reuse of wastewater in agriculture, firstly bacterial, viral and protozoan disease, and secondly helminthic diseases. For viral and protozoan disease, Table 2-4 summarises the WHO 2006 guidelines approach of assessing and managing the microbial risks from the use of wastewater in agriculture.

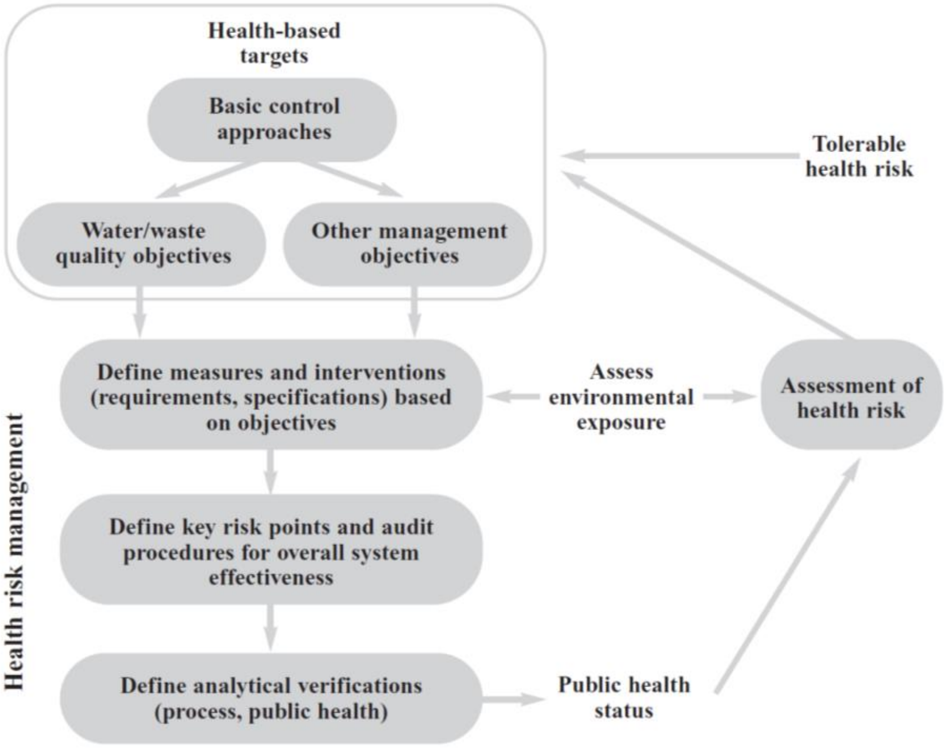


Figure 2-5 Stockholm framework for developing harmonized guidelines for managing water and sanitation related (WHO, 2006)

Table 2-4 Health-protection control measures and related pathogen reductions (Adapted from Schierling et al, 2010)

Step objective	Step activities
Step 1 Define tolerable maximum additional burden of disease	The metric for disease burden is the ‘disability-adjusted life year’ (DALY).2006 WHO Guidelines used a default value of $\leq 10^{-6}$ DALY loss per person per year (pppy) the same level of protection used in the WHO2004 guideline for drinking water. A more achievable value could be recommended for low- and middle-income countries are $\leq 10^{-4}$ DALY loss pppy at least as initial step for managing health risk
Step 2 Derive tolerable disease and infection risks	The tolerable risk of a disease per person per year is obtained from the equation: (tolerable DALY loss pppy ÷ DALY loss per case of the disease), and the tolerable risk of infection pppy from the equation: (tolerable disease risk ÷ disease/infection ratio)
Step 3 Conduct quantitative microbial risk analyses to determine required minimum total pathogen reductions	QMRA-Monte Carlo simulations are used to estimate the required minimum total pathogen reductions. The parameters values used in the QMRA-Monte Carlo simulations should be selected to reflect local circumstances
Step4 Determine how the required pathogen reductions are to be achieved	The pathogen reduction can be achieved by wastewater treatment for protecting the worker in wastewater irrigated fields but also could be achieved by Non-treatment options. For unrestricted additional post-treatment, health-protection control measures could be required to protect the consumer of wastewater-irrigated foods or increase the degree of wastewater treatment as shown in Table 2-9
Step5 Verification monitoring	The purpose of verification monitoring is to confirm that the required pathogen reduction is being achieved either by wastewater treatment or Health-protection Control Measures. A Hazard Analysis Critical Control Point (HACCP) system must be applied to monitor the efficacy of the health protection control measures listed in Table 2-9

2.6.1.2.1 Health-based targets

The guideline recommends applying a tolerable additional burden of disease of 10^{-6} disability-adjusted life year (DALY) loss per person per year (pppy) (see BOX 2-2) as the maximum level of health protection target from the use of wastewater in agriculture. This is the same level of protection used in the WHO 2004 guideline for drinking water (WHO, 2006). However, it has been recognised that this target might be too stringent for many developing countries. Thus the more realistic level of $\leq 10^{-5}$ DALY loss pppy or even $\leq 10^{-4}$ of DALY loss pppy could be sufficient for health protection from wastewater exposure or the consumption of wastewater irrigated food (Mara et al., 2010c). A maximum tolerable additional DALY loss of 10^{-4} corresponds to an additional disease risk of 10^{-2} that is equivalent to an additional episode of diarrhoeal disease per individual per 100 years (Mara et al., 2010b).

These less strict targets would be the key to adoption of the WHO2006 guidelines in middle and low-income countries as these levels could easily be achieved by a combination of a low level of treatment and health protection control measures. For instance setting $\leq 10^{-4}$ of DALY loss pppy as a target for restricted reuse could be achieved by a lower level of wastewater treatment that provides 1-2 log unit reduction of pathogens (Mara et al., 2010c).

To conduct a microbial risk assessment, the established tolerable maximum additional burden should be converted to the tolerable risk of a disease and tolerable risk of infection per person per year, for one or more of the key pathogens, as follows (WHO, 2006):

$$\text{Tolerable disease risk pppy} = \frac{\textbf{Tolerable DALY loss pppy (i.e.,} \mathbf{10^{-6}}\textbf{)}}{\textbf{DALY loss per case of disease}} \qquad \text{Equation 2-1}$$

$$\text{Tolerable infection risk pppy} = \frac{\textbf{Tolerable disease risks pppy}}{\frac{\textbf{Disease}}{\textbf{infection}}\textbf{ratio}} \qquad \text{Equation 2-2}$$

BOX 2-2 Disability-adjusted Life Years (DALYs)

DALYs are a measure of the health of a population or burden of disease due to a specific disease or risk factor.

DALYs attempt to measure the time lost because of disability or death from the disease compared with a long life free of disability in the absence of the disease. DALYs are calculated by adding the years of life lost (YLL) due to premature death to the years lived (YLD) with a disability.

YLL are calculated from age specific mortality rates and the standard life expectancies of a given population.

YLD are calculated from the number of cases of the disease multiplied by its average duration and a severity factor ranging from 1 (death) to 0 (perfect health) based on the disease. For example, watery diarrhoea has a severity factor from 0.09 to 0.12, depending on the age group.

DALYs are an important tool for comparing health outcomes because they account for not only acute health effects but also for delayed and chronic effects i.e., they include both morbidity and mortality. When risk is described in DALYs, different health outcomes (e.g., fatal cancers and non-fatal diarrheal diseases) can be compared and risk management decisions prioritized.

Source: (WHO, 2006)

2.6.1.2.2 Quantitative Microbial Risk Analysis

Quantitative Microbial Risk Analysis (QMRA) is the foundation of the rational risk assessment and management framework adopted in the guideline. QMRA combined with Monte Carlo simulation are used to estimate numerical values for the annual risk (probability) of disease or infections resulting from the exposure to a certain number of specific pathogens. These probabilities are used to determine the required reduction of pathogens to meet the health protection targets (Navarro et al., 2010).

The results from QMRA can also be used to assess the relative effectiveness of different strategies for microbial risk management (Scheierling et al., 2010). The application of QMRA depends largely on the availability of dose-response information. Other key information such as frequency and concentration of pathogens in wastewater, cropping pattern, transmission pathway, disease-infection ratio and the health impacts in term of the rate of morbidity or mortality due to diseases are also essentail for this technique to be used calculating the probability of infection from exposure to specific pathogens (Navarro et al., 2010). In the guidelines, three key pathogens have been chosen to be included in QMRA and determine the infection risks, these are rotavirus (a viral pathogen), *Campylobacter* (a bacterial pathogen), and *Cryptosporidium* (a protozoan pathogen). These pathogens have been chosen as reference pathogens for two reasons, firstly because their DALY loss per case of disease and the corresponding disease/ infection ratios are well known (Table 2-5), and secondly because the dose-response data needed for QMRA are available (WHO, 2006, Scheierling et al., 2010, Mara and Bos, 2010).

Table 2-5 DALY losses, disease risks, disease/infection ratios and tolerable infection risks for rotavirus, Campylobacter, and Cryptosporidium (WHO 2006)

Pathogen	DALY loss per case of disease	Tolerable disease risk pppy equivalent to 10^{-6} DALY loss pppy[a]	Disease/ infection ratio	Tolerable infection risk pppy[b]
Rotavirus: (1) IC[c]	1.4×10^{-2}	7.1×10^{-5}	0.05[d]	1.4×10^{-3}
Rotavirus: (2) DC[c]	2.6×10^{-2}	3.8×10^{-5}	0.05[d]	7.7×10^{-4}
Campylobacter	4.6×10^{-3}	2.2×10^{-4}	0.7	3.1×10^{-4}
Cryptosporidium	1.5×10^{-3}	6.7×10^{-4}	0.3	2.2×10^{-3}

a. Tolerable disease risk = 10^{-6} DALY loss per person per year (pppy) ÷ DALY loss per case of the disease.
b. Tolerable infection risk = disease risk ÷ disease/infection ratio.
c. IC, industrialized countries; DC, developing countries.
d. For developing countries, the DALY loss per rotavirus death has been reduced by 95 percent to discount deaths occurring in children under the age of two who are not exposed to wastewater-irrigated foods. The disease/infection ratio for rotavirus is low as immunity is mostly developed by the age of three

DALY values from Havelaar and Melse (2003)

To Conduct QMRA-MC risk simulations for determination of the required minimum total reductions for the reference pathogens the guidelines developed two main exposure scenarios:

1) **Unrestricted**: For consumption of wastewater-irrigated crops, that are eaten uncooked. The guidelines used lettuce and onions for non-root crop and root crop respectively.
2) **Restricted**: Ingestion of wastewater-saturated soil particles by farmers and field workers, this scenario assumes that wastewater-saturated soil may contaminate farmers' or field workers' fingers and subsequently some pathogens may be transmitted to their mouth and then be ingested. It has been reported that the quantity of soil that could be ingested in this way is up to ~100 mg per person per day of exposure (Haas et al., 1999, WHO, 2001). Two sub-scenarios are used as follows:

- **Highly mechanized agriculture,** particularly in industrialised countries where tractors and associated equipment are used for ploughing, sowing, and harvesting. In this senario it is assumed that farmers and field workers wear gloves, footwear, and other protective clothing when working in wastewater-irrigated fields.

- **Labour-intensive agriculture**, particularly in developing countries where machines such as tractor are not commonly used, and the farmer is most likely not to wear gloves, footwear, and other protective clothing when working in wastewater-irrigated fields (WHO, 2006).

Annex 1 provides the results of QMRA-MC risk simulations for different scenarios used in the guidelines.

Recently, a more rigorous method for estimating annual infection risks from QMRA-Monte Carlo simulation has been developed by Karavarsamis and Hamilton 2009 (Mara et al., 2010c). This method is based on daily variation for estimating median annual infection risks in which the iteration number is set equal to the number of exposure days per year. This approach would be more robust than estimating annual infection risk for any one day of exposure (as in the procedure used in the 2006 WHO guidelines). A comparison between the results from the procedure suggested in the guidelines and this method is shown in Table 2-6. The values of median annual risk are similar for both methods, whereas Karavarsamis and Hamilton (date) provide a lower estimate (up to an order magnitude) of the 95-percentile annual risks values than the WHO 2006 method (Mara et al., 2010c).

However, for the reference viral pathogen, it has been found that norovirus (formerly called Norwalk virus) has a very high infectivity and is the major viral pathogen causing diarrhoea in adults whereas rotavirus is the main viral pathogen affecting young children (under five years old). Since the adults are more likely to be exposed to wastewater used in agriculture, norovirus is considered as a better reference viral pathogen than rotavirus (Mara and Bos, 2010, Scheierling et al., 2010).

Table 2-6 Comparison of the Karavarsamis and Hamilton (2009) and WHO (2006) methods for determining annual rotavirus infection risks pppy from the consumption of wastewater-irrigated lettuce [a] (Adapted from Mara et al, 2012c)

Wastewater quality	**Rotavirus infection risk per person per year**			
(E. coli per 100ml)	WHO2006		Karavarsamis & Hamilton (2009)	
	Medium	95%	Medium	95%
10^7 -10^8	1	1	1	1
10^3 -10^4	0.29	0.7	0.36	0.39
100-1000	3.4×10^{-2}	0.11	4.5×10^{-2}	4.9×10^{-2}
10-100	3.5×10^{-3}	1.3×10^{-2}	4.6×10^{-3}	5.1×10^{-3}
1-10	3.4×10^{-4}	1.2×10^{-3}	4.6×10^{-4}	5.1×10^{-4}

a. Estimated by 10,000 Monte Carlo simulations. Assumptions: 100g lettuce eaten per person per two days; 10–15ml wastewater remaining on 100g lettuce after ; 0.1–1 rotavirus per 10^5 *E. coli*; no pathogen die-off; $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$.

2.6.1.2.3 Recommended levels of pathogens reduction in the Guideline

Based on the results from the health risk assessment using epidemiological evidence with Monte Carlo-QMRA (Table 2-7, Annex 1), the guideline makes the following recommendations:

- For restricted use, to protect agricultural field workers and their families from the exposure to wastewater a 3-4 log unit pathogen reduction against the risks of viral, bacterial and protozoan infections, is required.
- For unrestricted use, it recommends a 6-7 log units pathogen reduction to protect the consumer of wastewater-irrigated food against the risks of viral, bacterial and protozoan infections.

Table 2-7 Health based target for treated wastewater [a] (WHO 2006)

Exposure scenario	Health-based target (DALY PPPY)	Design tolerable level of rotavirus infection risk (pppy)	Log pathogen reduction needed
Unrestricted	$\leq 10^{-6}$	10^{-3}	
Lettuce			6
onion			7
restricted	$\leq 10^{-6}$	10^{-3}	
Highly mechanized			3
Labor intensive			4

a. Rotavirus reduction

In order to protect farming worker and consumers of wastewater irrigated food against the risks of helminthic infection, the guideline recommended ≤1 helminth egg per litre of wastewater (WHO, 2006). The log unit reduction required to achieve the recommended target of ≤1 helminth egg per litre of wastewater depends on the number of eggs in raw wastewater (Table 2-8) (WHO, 2006). For example, in the ascariasis-hyperendemic areas (~1000 eggs per litter of wastewater) a 3-log reduction of Ascaris eggs is required (Mara et al., 2010a).

Table 2-8 The reduction of helminth eggs for different helminth egg number in raw wastewater (WHO 2006)

Heath protection measure	Number of helminth eggs per liter of raw wastewater	Required helminth egg reduction by treatment
Treatment	10^3	3
	10^2	2
	10	1
	≤1	0
Treatment and produce washing		
	10^3	2
	10^2	1
	10	0
	≤1	0

Based on epidemiological studies in Mexico, it has been found that these recommendations only protect adults and willnot protect children under the age of 15 years. Thus lowering the value to ≤0.1egg per litre is required in the case of children under the age of 15 years are exposed to wastewater or if the soil conditions are favourable to egg survival (WHO, 2006). Currently, as the Ascaris dose-response data is now available (Navarro et al., 2009), it becomes possible to use Ascaris as the helminthic pathogen indicator and use QMRA to determine the required log unit reduction of Ascaris to protect children under the age of 15 years (Mara and Sleigh, 2010a).

2.6.1.2.4 Risk management approach

The guideline has adopted a multiple barriers approaches for risk management as illustrated in Figure 2-6. This approach provides a code for good management practices that ensure the safe use of wastewater in agriculture, particularly in developing countries, where conventional treatment is insufficient not available, or using QMRA is not possible due to any reasons such as missing data or research capacity (Mara and Bos, 2010, Ilic et al., 2010).

To ensure greater health protection to workers in wastewater irrigated fields and their families as well as the consumers of food produced through wastewater irrigated crops the guidelines recommended a combination of non-conventional wastewater treatment and other health protection control measures (Ilic et al., 2010, WHO, 2006). These control measures are based on good agriculture practices, good processing practices, and good hygiene practices, (WHO, 2006, Ilic et al., 2010). Figure 2-7 presents examples of hazard barriers for wastewater, incrementally building up to reach health-based targets.

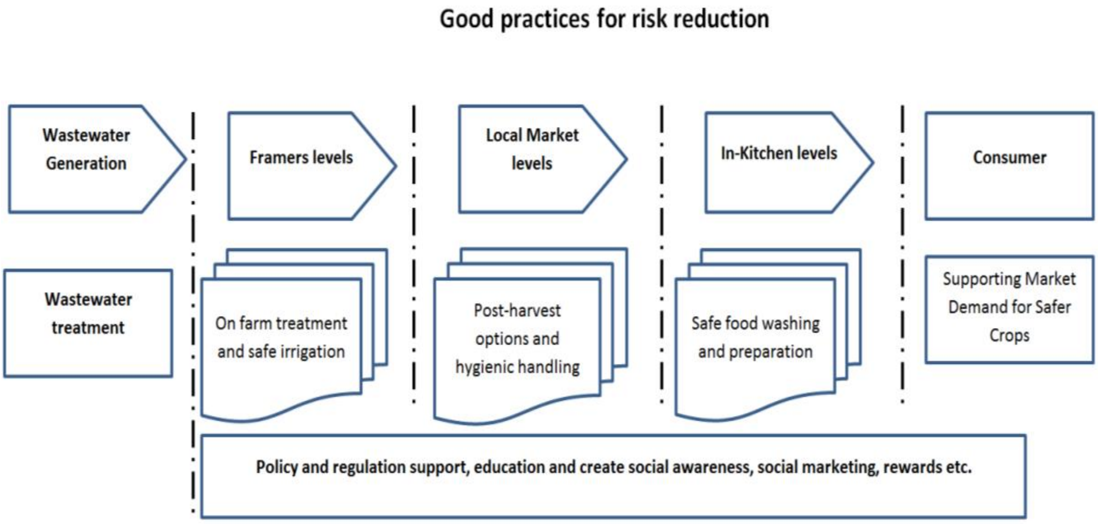


Figure 2-6 The multiple barriers approaches to microbial (Ilic et al. 2010)

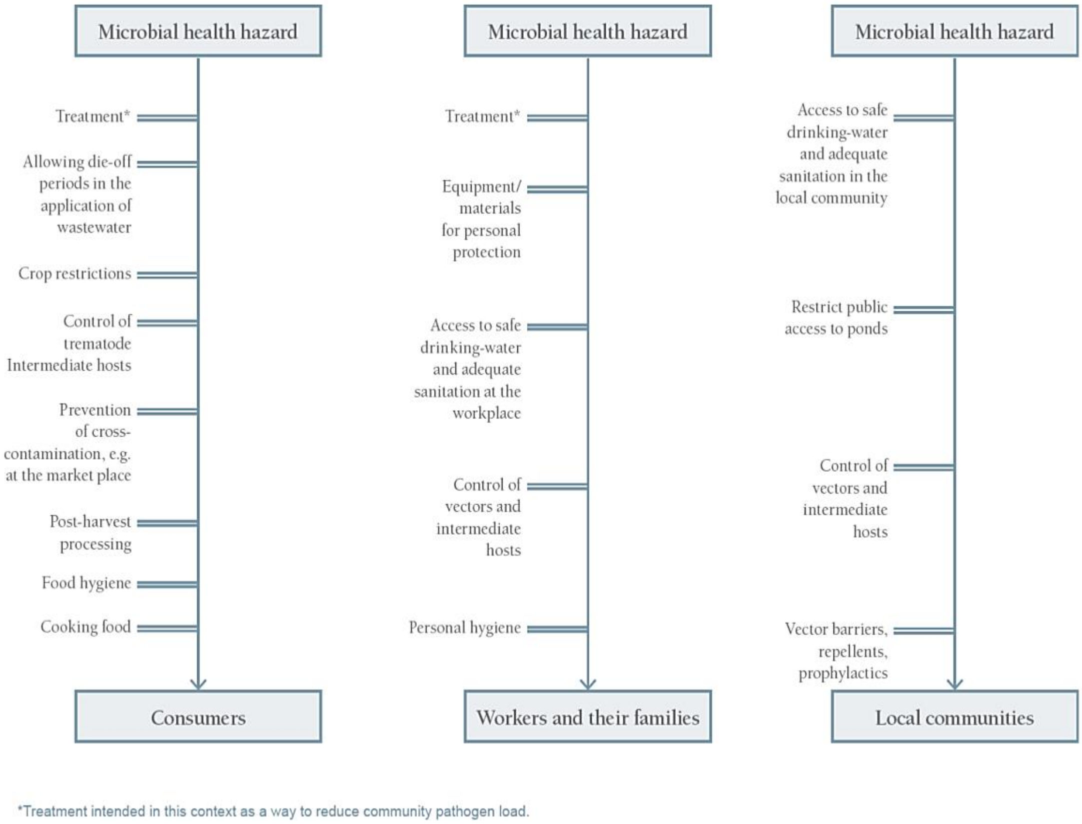


Figure 2-7 Examples of hazard barriers for wastewater, incrementally building up to reach health-based targets(Bos, 2010)

2.6.1.2.5 Achieving the Required Pathogen Reduction

The 2006 WHO guidelines allow health risks to be managed through treatment and non-treatment options as presented in Table 2-9 (Mara et al., 2010a). These measures are aiming to reach the health-based target of 10^{-6} DALY loss per person per year by accumulative pathogen reduction of 6-7log units, (particularly for unrestricted wastewater reuse). Figure 2-8 illustrates the different possible risk management strategies that can be used to achieve the health protection target of 10^{-6} DALY loss per person per year (WHO, 2006).

Options for the reduction of viral, bacterial and protozoan pathogens by different combinations of health protection measures that achieve the health-based target of $\leq 10^{-6}$ DALYs per person per year. (WHO, 2006)

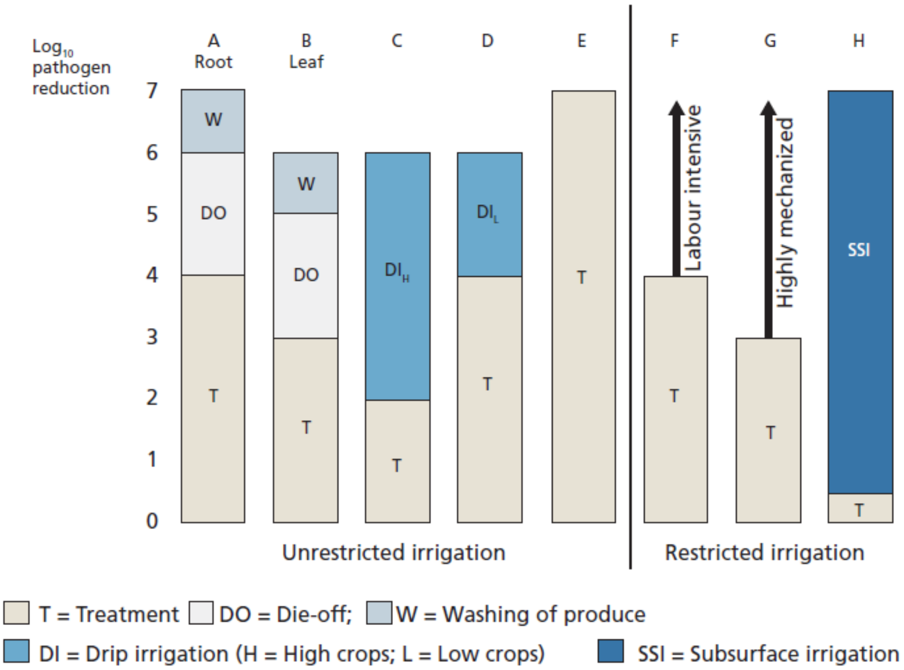


Figure 2-8 Example of different risks management strategies (WHO 2006)

Adopting this approach provides greater flexibility in risk control and management, as well as facilitating progressive implementation of the 2006 WHO guideline especially in countries where the recommended targets are not feasible due to their particular socio-economic context. In these circumstances, lower health based targets could be established under strict monitoring to ensure their implementation with the intention to improve the target incrementally toward international recommendations (Bos et al., 2010). For example, a Ghana study shows that using low cost protection measures such as cessation of irrigation post to harvesting, safer irrigation methods, farm-based treatment (e.g. sand filters and on-farm sedimentation ponds), and post-harvest measures can potentially lead to significant reductions in helminth eggs and other pathogens, especially if they are used in combination as they would have a cumulative effect (Drechsel et al., 2008)

Table 2-9Health-protection control measures and associated pathogen reductions (Mara et al. 2010a)

Control measure	Pathogen reduction (log unit)	note
A. Wastewater treatment	1−7	Pathogen reduction depends on type and degree of treatment selected.
B. On-farm options		
Crop restriction (i.e., no food crops eaten uncooked)	6−7	Depends on (a) effectiveness of local enforcement of crop restriction, and (b) comparative profit margin of the alternative crop(s).
On-farm treatment:		
a. *Three-tank system*	1-2	Operated in sequential batch-fed mode
b. *Simple sedimentation*	0.5-1	Sedimentation for ~18 hours
c. *Simple filtration*	1-3	Value depends on filtration system used.
Method of wastewater application		
a. *Furrow*	1-2	Crop density and yield may be reduced
b. *Low-cost drip*	2-4	2-log unit reduction for low-growing crops, and 4-log unit reduction for high-growing crops.
c. *Reduction of splashing*	1-2	Farmers trained to reduce splashing when watering cans used (splashing adds contaminated soil particles on to crop Surfaces that can be minimized).
Pathogens die off	0.5-2	Die-off between last and harvest (value depends on climate, crop type, etc.).
C. Post-harvest options at local markets		
Overnight storage in basket	0.5-1	Selling produce after overnight storage in baskets (rather than overnight storage in sacks or selling fresh produce without overnight storage).
Produce preparation before sale	1-2	(a) Rinsing salad crops, vegetables, and fruit with clean water.
	2-3	(b) Washing salad crops, vegetables, and fruit with running tap water.
	2-4	(c) Removing the outer leaves on cabbages, lettuces, etc.
D. In-kitchen produce-preparation options		
Produce disinfection	2-3	Washing salad crops, vegetables, and fruit with an appropriate is a disinfectant solution and rinsing with clean water.
Produce peeling	2	Fruits, root crops
Produce cooking	5-6	Option depends on local diet and preference for cooked food.

2.6.2 Assessing and Managing Chemical Risks

2.6.2.1 Health risks

Wastewater contains a wide variety of toxic organic, and inorganic chemicals that may be taken up by the crops and pose a risk to human health. These chemicals include heavy metals, priority organic pollutants (such as pesticides like DDT, 2,4-D, Aldrin etc, and industrial compounds like phthalates PCBs, on –ionic detergents), disinfection by-products, synthetic and natural hormones, human and veterinary pharmaceutical residues and their metabolites, and residues of personal care products (PCPs)(WHO, 2006). Generally, using wastewater in agriculture is less certain to contribute to direct health impacts from such chemicals hazards unless the wastewater used for irrigation is heavily contaminated with industrial discharges (WHO, 2006, Hamilton et al., 2007)

While the risks from pathogenic microorganisms have usually predominated in most of the existing guidelines for safe use of wastewater in agriculture, the health risks associated with chemicals in wastewater have be paid much less attention. This may be due to the immediate effects of microbiological components on public health compared to the longer term risks posed by chemical exposure (WHO, 2006, Bos et al., 2010). Another explanation may be the difficulty in assessing the health impacts of toxic chemicals (such as heavy metal and toxic organic compounds and emerging contaminants) in wastewater due to their much longer latency period (Bos et al., 2010, Hamilton et al., 2007). Other factors may also contribute to the difficulty in assessing the health risks from chemicals including the fact that there is a very large range of chemicals to consider some which may be toxicants or carcinogens (Hamilton et al., 2007). In addition, many of these chemicals can be difficult to detect (Bolong et al., 2009). Also, the possibility of the existence of other potential unknown chemicals-of-concern makes it difficult to estimate the removal of all these chemicals under all available treatment technologies or environmental conditions (Toze, 2006b, Bergman et al., 2013). Finally, their transmission through the food chain is poorly understood for many chemicals (Qin et al., 2015, Bergman et al., 2013).

The existing chemical guidelines for safe reuse of wastewater such as WHO2006 were developed to prevent pollutant accumulation in the receiving soil, and maximize the soil’s capacity to assimilate dangerous chemicals. It recommends numerical limits of maximum permissible pollutant concentrations in the soil for a range of organic and inorganic constituents based on the principle of environmental sustainability (see Annex 2), these recommendations could be difficult to achieve for most developing countries. Chemical guidelines and quantitative chemicals risk assessment for health protection will become more important in the future especially in developing countries where industrialization is increasing and wastewater from industrial sources are usually mixed with sewage water.

2.6.2.2 Environmental risks

Environment risks are different from health and social risks as they focus on environmental capital (i.e. the capacity of the ecosystem receiving the chemicals loads) Inappropriate management of wastewater can contribute to serious environmental problems especially in developing countries where untreated or partially treated wastewater is used in agriculture (Pescod, 1992, Ayers and Westcot, 1985, WHO, 2006, Simmons et al., 2010). Wastewater could present negative impacts on the properties of soils and soil fertility, crops qualities and yields, groundwater, surface water, and the aquatic ecosystem. The magnitude of potential impacts depends on the concentration of the chemicals, their solubility, and their inherent toxicity among other factors such as rate and frequency of wastewater application, type and target yield, soil properties and condition, the vulnerability of aquifer, climate, and technology level and the social-economic conditions of farmers (WHO, 2006).

In order to ensure good crop yields and minimise the environmental risks associated with the chemical constituents in wastewater, guidelines such as the FAO guidelines for the evaluation of irrigation water quality and the WHO2006 recommend quality standards (Annex 2) and management approaches for good agricultural practices which address the long-term impact on soils, crop production, water bodies and farm management (WHO, 2006, Ayers and Westcot, 1985). In general, environmental risk reduction and management could be categorised into wastewater treatment technologies, on-farm treatment options and finally farm-based measures to mitigate environmental risk in places where low-quality water is used. The following sections present a review of available management strategies for environment risk reduction.

2.6.2.2.1 Management of Excessive salts

Removing salts from wastewater for irrigation purposes is prohibitively expensive so therefore, there is a need for specific measures and management strategies to prevent and control the effects of salinity and sodicity during irrigation with wastewater.

One important option for salinity control is the regular application water for effective leaching to transfer solutes through the soil profile and ensure the leaching of excess salt below the root zone (Carr, 2011, Maas and Grattan, 1999, Letey et al., 2011, Hillel, 2000). To achieve the leaching requirements, an adequate soil drainage system is an essential prerequisite. This can be facilitated through natural drainage if the soil has sufficient storage capacity or permeable subsurface layers, or via artificial drainage systems. In addition to soil drainage, adequate groundwater depth and land levelling are also important components to control salinity in the root zone (Simmons et al., 2010).

A number of studies have found crop selection to be the principal factor for the sustainability of wastewater irrigation since certain crops can be irrigated with wastewater without any negative impact on yield while other show adverse effects. A number of field crops, fruit trees, forage grasses and others have been identified in the literature to suit various salt-affected environments (Simmons et al., 2010, Ayers and Westcot, 1985, Maas and Grattan, 1999, Grattan et al., 2004). As it was mentioned earlier, salt tolerance can be divided into four classes including those that are sensitive (Sesame, Carrot, Onion, Almond, and Apple), moderately sensitive (Corn, Peanut, Alfalfa, Tomato, Cucumber and Grape), moderately tolerant (Sorghum, Soybean, Wheat, Squash, Fig and Olive and tolerant (Barley, Cotton, Oat, Date palm and Currant) (Maas and Grattan, 1999). Crop choice will depend on soil conditions, water quality, and climate. Suitable crops should also demonstrate the following characteristics: (i) high water and N demand, and tolerance to salinity; (ii) good potential end use; (iii) good marketability (da Fonseca et al., 2007).

Another management option to mitigate the salinity impact of wastewater irrigation is the use of the wastewater in conjunction with fresh water, if available, via blending or alternating approaches which provide more flexibility to suit different situations (Ayers and Westcot, 1985, Malash et al., 2005, Yu et al., 2012). Different field studies have evaluated various aspects of these approaches and one study suggested that the optimum ratio of mixing fresh water to wastewater is between 2:1 and 1:2 for plant growth (Yu et al., 2012). Another study carried out by Malash et al. (2005) found that a mixed management strategy with a 60% fresh water 40% saline water ratio in combination with a drip irrigation system gave the highest values of yield and growth in tomato production. An alternating strategy of fresh and saline water can also provide many advantages including the ability to grow a broad range of crops, flexibility to use conventional irrigation methods and control of soil salinity in topsoil during seedlings stage to a lower level over time.

Since most crops are sensitive during their seeding stage especially grains (barley, wheat, and rice) sesbania, cotton, tomato, corn, and sugar beets (Hanson et al., 1999); it may be possible to reduce the effects of salinity by using modifications of planting practice to minimise salt accumulation around the seeds. This may include sowing near the bottom of the sloping sides of furrows; increased plant density (the seedling rate per unit area) which could compensate for reduced germination; and growing seedlings with fresh water (Minhas, 1996, Ayers and Westcot, 1985).

The application method could also directly affect the efficiency of water use and the way salts accumulate in the soil profile. Some methods are more suitable for use with saline water than others. Several parameters in relation to risk reduction could be used to choose the most suitable method including leaf damage, salt accumulation in the root zone, ability to maintain high soil water potential and ability to handle saline water without significant yield loss. Each irrigation method has a combination of impacts on these parameters, which should be considered before any attempt to improve salinity and sodicity control by changing the irrigation method is undertaken (Maas and Grattan, 1999, Hillel, 2000, Pescod, 1992).

In the case of sodicity problems, soil treatment is a particularly useful option to mitigate the effect of soil sodicity. Mitigating the effect of excess sodium on soil and crops can be achieved through improving soil physical properties and infiltration rate by adding chemical amendments such as gypsum (Simmons et al., 2010, Ayers and Westcot, 1985, Hillel, 2000). Leaving plant residues or adding organic matter to the field can also enhance the physical and chemical condition of soils irrigated with sodic water (Simmons et al., 2010).

Where available, water with a high electrical conductivity and an adequate proportion of divalent cations (mainly calcium) could also be used to improve sodic and saline-sodic water without the need for a calcium-supplying amendment (Simmons et al., 2010)

2.6.2.2.2 Management of Heavy metals

Although wastewater treatment is the best choice in managing wastewater for use in agriculture, biological treatments are generally designed to remove organic compounds and microorganisms and therefore the removal of heavy metals by biological treatment may be regarded as a side benefit (Chipasa, 2003). The efficiency of metal removal by biological treatment processes will vary depending on the types of metals which are present and their concentration. Physical, chemical and biological factors will also affect the outcome, for example, heavy metal removal from activated sludge depends on pH and dissolved organic matter and an increase in pH will increase the removal as metals precipitate as hydroxides (Chipasa, 2003). High concentrations of heavy metals can be toxic to microorganisms and reduce microbial activity resulting in an adverse effect on biological treatment processes (Chipasa, 2003). In recent years, various treatment technologies for heavy metal removal from sewage, industrial and mining waste effluents have been extensively studied. These technologies include chemical precipitation, ion-exchange, adsorption, coagulation, cementation, electrochemical treatment technologies, membrane filtration and reverse osmosis (Fu and Wang, 2011). Each of these methods offers many advantages and also limitations for their use for the removal of heavy metals from wastewater. For instance, chemical precipitation has traditionally been used for metal removal from aqueous solutions due to its simplicity and low capital and operational costs, however, its efficiency can be affected by pH and the presence of another ion, it is also ineffective when metal concentration is very low (Fu and Wang, 2011, Baysal et al., 2013). Ion exchange, membrane filtration, and adsorption are alternative methods which have been wildly studied for heavy metal removal. Ion exchange has successfully been used to remove heavy metals from wastewater. Membrane filtration and adsorption have a high efficiency for the removal of heavy metals from wastewaters with low concentrations of heavy metal. However, these technologies have high capital and operational costs which limit their use especially on a large scale especially in developing countries (Fu and Wang, 2011, Baysal et al., 2013).

The selection of the most suitable treatment method will depend on many factors including the metal concentration, other wastewater components, plant flexibility and reliability, capital investment and operational cost, and environmental impact.

In the absence of treatment options to remove heavy metals from wastewater, other management measures at farm level could be very useful to reduce heavy metal transfer into the food chain. However, these measures may be more effective on soils with low or medium levels of contamination. Each of them has advantages and drawbacks and the effectiveness of using one or combinations of these measures will depend on the specific site conditions. One of the most effective options is plant-based treatment and soil based treatment

Plant-based treatment includes growing of photo-remediation crops, growing industrial crops and selecting crops with low metals uptake. Certain plant species can be used to absorb and uptake trace elements from soil to above-ground biomass. These plants are known as hyperaccumulators and have the ability to accumulate high concentrations of metals up to 100 times greater compared to other non-accumulator plants grown in the same contaminated soil (Chaney et al., 2007). Currently, there are around 400 species categorized as hyperaccumulators of metals such as Thlaspi caerulescens, Thlaspi caerulescens, Aeolanthus biformifolius, and Alyxia rubricaulis (Cobbett, 2003, Chaney et al., 2007)

The cultivation of industrial plants including fibre plants (flax, cotton etc.) and energy crops (Salix trees and reed canary grass) has been considered as a valuable option for agricultural use in areas where soils are impacted by heavy metals (Puschenreiter et al., 2005). In addition to industrial plants, aromatic crops could be grown on heavy metals enriched soil without causing any significant risk of metals transfer from soil to oil and alteration in essential oil composition (Lal et al., 2013).

Selecting crops with low metals uptake could also be a very useful option to reduce any potential health risks via the food chain. Some crops such as leafy vegetables accumulate certain metals in their edible parts in greater amounts than non-leafy crops. Metals usually accumulate in leaves and roots more so than in the seeds and fruits, suggesting that legumes such as peas, and grains may be more appropriate crops than vegetables such as cauliflower, lettuce, spinach and carrots where heavy metals are present. In addition, fodder crops may be preferred since they pose a lower risk to human health as the process of transfer of metals via the food chain will be longer (Puschenreiter et al., 2005, Simmons et al., 2010).

Soil amendment is another farm-based measure that could mitigate against plant uptake of heavy metals. Soil amendment can be classified into the organic and inorganic amendment. Organic amendments such as farmyard manure (FYM), compost, biosolids or biosolid compost could effectively decrease the mobility and bioavailability of heavy metals in soils as a result of their high content of organic matter and high concentrations of P and Fe (Puschenreiter et al., 2005, Bolan et al., 2003). Inorganic amendments such as gypsum, lime $CaCO_3$, synthetic zeolites, phosphate material, Mn and Fe oxides and clay minerals are very effective in reducing metal mobility and bioavailability due to pH effects and the introduction of additional binding sites for heavy metals (Chen et al., 2003, Brown et al., 2004, Oste et al., 2002, Puschenreiter et al., 2005, Hettiarachchi and Pierzynski, 2002). Many of these amendments are by-products of industrial activities which are available in large amounts and are relatively inexpensive (Puschenreiter et al., 2005).

2.6.2.2.3 Management of Excessive Nutrients

Wastewater treatment plants typically provide various physical, chemical, and biological methods to improve effluent quality, however, nutrient removal from wastewater requires tertiary treatment and infrastructure that may be economically prohibitive (Carey and Migliaccio, 2009). An alternative approach that can also be used to remove excess nutrients from irrigation wastewater is to place on farm treatment options that work as effective sinks for nutrients such as the use of wetlands or duckweed ponds (Simmons et al., 2010, WHO, 2006, Qadir et al., 2015).

Excessive addition of nutrients particularly N could be avoided by selecting crops that can take advantage of high concentrations of nutrients such as fodder grass (Simmons et al., 2010) or utilising the practice of crop rotation to enable the removal of any excess nutrients (Hamilton et al., 2005). Hamilton et al. (2005) and Snow et al (1998,1999) claim that the risk of nitrate leaching to groundwater could be significantly reduced by appropriate matching of crops and plant production systems to climate and effluent characteristics. For instance, in arid zones, high yielding crops with large concentrations of nitrogen in their biomass (such as leafy vegetable and fodder grass) are likely to be more effective than tree plantations for decreasing nitrate leaching (Simmons et al., 2010, Hamilton et al., 2005).

Similar to salinity, over fertilisation from wastewater application could be reduced by using wastewater blended with fresh water or water with low nutrient concentrations. However, this option would only be possible when fresh water is available (Hamilton et al., 2005, Simmons et al., 2010, WHO, 2006, Qadir et al., 2015).

2.6.2.2.4 Management of toxic organic compounds and emerging contaminants

Many of the EDCs and PCPs tend to be resistant to conventional and even advanced wastewater treatment (WHO, 2006, Bolong et al., 2009, Fang et al., 2012, Wang et al., 2005). Certainly, existing wastewater treatment plants have not been designed for the removal of these pollutants and even if the best available treatment technology is adopted, only a part of a wide range of emerging contaminants can be removed especially by biological treatment (Luo et al., 2014). The reasons for this are numerous and include the fact that these pollutants have a wide range of chemical properties and their successful removal even in advanced treatment varies significantly (Bolong et al., 2009, Yan et al., 2010, Luo et al., 2014). Secondly, there is no existing regulation specifically targeted at wastewater or water treatment criteria for these range of compounds (Bolong et al., 2009, Fatta-Kassinos et al., 2011). Finally, the possibility of the existence of other potential unknown chemicals-of-concern makes it difficult to estimate the removal of all these chemicals under all available treatment technologies or environmental conditions (Toze, 2006b, Bergman et al., 2013). Due to the lack of current knowledge on the actual effects of these chemicals on humans and the environment (Bergman et al., 2013), the mitigation measures that could be applied to manage their risks are limited to pre-treatment or segregation of industrial discharges (WHO, 2006, Simmons et al., 2010), the promotion of more clean production in industries and education of society to use less toxic compounds (WHO, 2006, Simmons et al., 2010).

2.7 Challenges of Wastewater reuse in agriculture in Developing Countries

Despite the fact that wastewater use is a global phenomenon, and it has been increasingly recognized as a strategic alternative to fresh water in augmenting agricultural water supplies particularly in arid and semi-arid zones, in many developing countries, its effective implementation is nevertheless quite complex. In addition to the challenges associated with health and environmental risk assessment and reduction, wastewater reuse strategies are facing many other challenges including technical, legal and institutional, economic, and social challenges. This section highlights some of the challenges and the obstacles to wastewater reuse in agriculture in developing countries.

2.7.1 Wastewater generation, treatment, and technical challenges

Many cities in developing countries have inadequate sanitation capacities and poor wastewater infrastructures due the rapid expansion of urbanization which makes the management of urban wastewater a tremendous challenge. Some specific examples from the Middle East and North Africa include Syria, Libya, Lebanon, and Morocco where the lack of treatment capacity has resulted in much of the wastewater collected being directly discharged untreated into the sea or other surface water bodies, or on land, and consequently limits the potential of wastewater reuse (Condom et al., 2012, Jagannathan et al., 2009). Another example comes from Asia where only 24% and 2% of the urban wastewater is treated in India and Pakistan respectively (Qadir et al., 2010). In West African, it was estimated that less than 10% of wastewater generated is collected in a sewerage network and treated to primary or secondary treatment.

The selection of wastewater treatment options that are environmentally sustainable, suitable to local conditions and cost effective is one of the critical obstacles for wastewater reuse in developing countries (Jagannathan et al., 2009, Condom et al., 2012). Large centralised wastewater collection and treatment facilities have proven difficult to sustain in many developing countries due to the relatively high capital investment and cost-recovery, challenges associated with governance, and overemphasis on technologically driven processes (Jagannathan et al., 2009, Condom et al., 2012, Wichelns et al., 2015)

Additionally, many treatment facilities in developing countries are plagued by inadequate technical knowledge and the skills required for operation and maintenance (O&M) and many are operated beyond their design capacity. These conditions lead to a reduction in the treatment efficiency and it then become difficult to meet the quality requirements for wastewater reuse for irrigation. All these factors contribute to worsening treatment reliability and discredit wastewater reuse possibilities (Choukr-Allah and Hamdy, 2003, Jagannathan et al., 2009, Wichelns et al., 2015). For long-term operation and financial sustainability, decentralised systems have been promoted in many regions particularly in Africa and South Asia (Wichelns et al., 2015, Qadir et al., 2010). Although these systems provide more flexibility and claim to be more cost effective, they still have their challenges, for example, a study in Ghana shows that only 7 out of 44 small treatment facilities were functional and the effluent quality was likely to be lower than the designed standard(Qadir et al., 2010)

2.7.2 Economic and financial challenges

The lack of complete economic analysis is one of the major obstacles for successful wastewater reuse strategies. The decision to promote any wastewater reuse project should consider all the economic aspects and benefits. In many economic appraisals of wastewater reuse, economic analysis rarely includes all relevant economic aspects and rarely goes beyond financial feasibility analysis (Jagannathan et al., 2009, Choukr-Allah and Hamdy, 2003, Scheierling et al., 2010). While the direct benefits of wastewater reuse may be easy to evaluate, indirect effects and non-monetary issues such as the health and environmental effects of a wastewater reuse project on downstream communities is hardly taken into account when performing an economic appraisal of wastewater reuse projects (Scheierling et al., 2010).

Furthermore, much wastewater reuse planning tends to overlook many of the other costs such as regulatory costs, public information and education, the opportunity cost of water for other users, and addressing compensation. For example, when treated or untreated wastewater is already been used for some other purpose (indirectly or unplanned), its opportunity cost should be included when considering planned reuse (Jagannathan et al., 2009, Choukr-Allah and Hamdy, 2003). In many cases economic analysis does not take into account the impacts of reuse projects on certain stakeholder groups affected by these projects and fails to address compensation costs, for example, farmers may have access to untreated wastewater, to which they may lose access after a reuse project is instigated. Similarly, the farmer may prevent unrestricted irrigation resulting in a loss of income from reuse (Jagannathan et al., 2009, Choukr-Allah and Hamdy, 2003).

Another challenge is the difficulty to draw up financing mechanisms to determine the source of revenues and to clarify the distribution of costs (including cost transfers to other sectors) and benefits between different stakeholders of the projects (Choukr-Allah and Hamdy, 2003, Jagannathan et al., 2009, Condom et al., 2012, Wichelns et al., 2015). In many developing countries, wastewater reuse requires indefinite government commitment for subsidies due to inadequate tariff policies and limited financial capacity (Condom et al., 2012, Wichelns et al., 2015). For example, in the Middle East and North Africa, households do not directly perceive the environmental benefits for wastewater treatment and reuse, so as wastewater is collected and conveyed far from urban area the servers considered to be adequate; therefore, government normally tend to find collecting fees for wastewater treatment is a challenging. On the other hand, the fresh water price for irrigation use in many cases does not reflect its scarcity or even the actual cost of supply. Therefore, it is sold at a cost that is below the cost by which wastewater could be treated and reused. Also, most of these countries do not have charges or controls on groundwater withdrawals and as a result this option is particularly popular. Furthermore, water demands for irrigation usually do not match with the all year round supply of wastewater and therefore there will be periods of the year when demand for treated wastewater for agricultural use is low. Thus it is impossible for utilities to recover the financial costs of treatment, conveyance regulation and monitoring without the long-term commitment from the government to provide subsidies (Jagannathan et al., 2009, Condom et al., 2012)

2.7.3 Institutional context, policies, and regulations

Developing coherent national policies and implementing wastewater reuse strategies with integrated water resource management is a major challenge in developing countries, where there is a lack of institutional support and a common authority for collection, treatment and reuse (Condom et al., 2012, Wichelns et al., 2015). In many countries in Asia, Africa and Latin America the responsibility of wastewater management is shared between several departments and agencies either governmental, private or both (such as in Syria where five ministries are involved in wastewater management) (Condom et al., 2012, Wichelns et al., 2015). In addition, in most of these countries, there is a lack of coordination regarding policies and institutional aspects pertaining to wastewater reuse (Condom et al., 2012, Wichelns et al., 2015). Institutional arrangement in most of these cases are not adequately clear and there are overlapping responsibilities across scattered institutions. This may lead to bureaucratic limitation and increase the transaction costs for effective management of wastewater (Wichelns et al., 2015).

Another important issue for sustainable wastewater reuse strategies is applying realistic standards and enforceable regulations. In general, in the majority of developing countries, wastewater reuse guidelines and standards are non-existent or not flexible enough to take into account local conditions (Condom et al., 2012, Wichelns et al., 2015). In countries where untreated wastewater reuse in agriculture is a strong tradition and the capacities for treatment are lacking, adopting restrict international standards (such as WHO1989) serve no purpose as they are difficult to achieve and farmers tend to discredit planned reuse (Raschid-Sally and Jayakody, 2009, Condom et al., 2012). For example, banning the use of treated wastewater for irrigation of raw crops in The West Bank, Tunisia, Egypt and Syria motivated many farmers to go back to unplanned reuse practices (Condom et al., 2012). Furthermore, even where guidelines exist, the absence of legislation or incomplete legislation and regulations hinders effective wastewater reuse in agriculture (Condom et al., 2012, Wichelns et al., 2015). Many countries have an incomplete legal framework and a problem of effective regulatory enforcement, particularly with respect to tariffs and operational regulations, obligations of local government and the end user, and monitoring and control of effluent quality (Condom et al., 2012, Wichelns et al., 2015). This is further confirmed in many countries in West Africa and the Middle East where reuse of wastewater is often forbidden for unrestricted irrigation and the absence of effectively enforcing regulation has resulted in unofficially tolerated reuse practices (Condom et al., 2012, Raschid-Sally and Jayakody, 2009)

2.7.4 Public perception

Even when wastewater reuse projects are well designed, financially feasible and risk management measures well incorporated, they can fail if social and cultural dimensions were not taken into account (Wichelns et al., 2015). The acceptance of the safe use of wastewater projects is not straightforward even when key factors such as water scarcity, treatment capacity, and educational programs are in place (Wichelns et al., 2015). Public perception can support or constrain the development of wastewater reuse projects which can be influenced by many factors including public awareness and participation, availability of alternative water sources, religious and cultural aspects and/or social-economic aspects (Abdala et al., 2012).

Achieving general acceptance of wastewater reuse require active public involvement from the planning stages to the full implementation (Wichelns et al., 2015, Choukr-Allah and Hamdy, 2003). Increasing public awareness of potential gains and risks can help to promote a safe and productive use of wastewater in agriculture. Several studies have shown that public awareness and education are fundamental factors associated with the level of acceptance of such projects. For example, in Greece and Kuwait, the willingness to accept wastewater reuse increased with educational attainment (Tsagarakis and Georgantzis, 2003, Alhumoud et al., 2010). In many developing countries risk awareness is among of the top challenges for the safe use of wastewater in agriculture. Many farmers and consumers in developing countries have a lack of understanding about the potential risks especially from contamination (such as pathogens and chemicals) from the use of untreated or partially treated wastewater (Qadir et al., 2010, Wichelns et al., 2015). Studies in West Africa show that consumers and traders generally have low risk perception which tends to be limited to the visible quality characteristics such as size, colour, and product cleanliness (Wichelns et al., 2015).

When there is a choice, even with advanced treatment being used and the risks well managed, conventional fresh water sources remain the favoured choice because they are seen as safer, and less restrictive. In some cases (such as the Middle East and North Africa countries) this option may be less expensive as they are often subsidized. For instance, countries like Tunisia, Jordan and Syria farmers prefer alternative fresh water sources when they exist compared to treated wastewater that comes with constraints and risks (Condom et al., 2012). While the availability of fresh water may be a significant disincentive for the use of treated wastewater, the case can be very different when the unplanned use of wastewater for irrigation is a common practice, especially if the key driver is income and not safety (Wichelns et al., 2015). There are many cases where the farmer's preference is to use untreated wastewater more than fresh or treated water. In Pakistan, farmer prefers to irrigate with untreated wastewater more than treated wastewater due to increased salinity that occurs in treatment ponds (Ensink et al., 2002). In Bangladesh, although the farmers are aware of the risks associated with wastewater irrigation, wastewater is still preferred due to its fertiliser value and lack of other reliable water sources that are available all year round (Mojid et al., 2010). Also, in Latin America, the main driver for using untreated wastewater is its fertiliser values, for example in Mexico farmers seek to use wastewater more than rainwater due to its availability all year round and its fertiliser value (Jiménez et al., 2010a, Jimenez and Asano, 2008)

In some societies, there may be deep rooted social or culture barriers to wastewater reuse. For example in places where there is no previous contact with wastewater reuse, despite the advanced treatment technologies, wastewater reuse is often rejected due to feelings such as disgust,, concern about potential health and environmental impacts, risk of devaluation of property, concern about product qualities and value, and changes to water and soil use (Raschid-Sally and Jayakody, 2009, Abdala et al., 2012). Also in some countries such as Tunisia, Jordan, and Kuwait religious concern is one of the reasons for farmers' rejection or hesitation to use wastewater for irrigation (Wichelns et al., 2015)

The lack of social or economic incentives for changing practice is the one of the greatest challenges, especially in low-income countries. Effective adaptation of risk reduction measures depends on the financial benefits and costs to the livelihoods of farmers who depend on the direct use of wastewater (Wichelns et al., 2015, Bos et al., 2010). Generally, in developing countries, farmers are concerned about business-related risks such as loss of income, additional investment (capital, labour, and land) and land-tenure issues more than the occupational risks or the risks to consumers. Studies carried out in poor communities conclude that farmers usually prefers a slight change in their current practice or changes that require low investment (Bos et al., 2010). A study conducted in Ghana found that cost/labour saving and market incentives are the most motivating factors in adopting best agriculture practices in the long-term (Wichelns et al., 2015).

2.8 Conclusion

Wastewater can be viewed as both a waste to be disposed of and a renewable resource. On the one hand, the stringent standards to ensure environmental sustainability make disposal of wastewater a major challenge particularly in large metropolitan areas (Hussain et al., 2002). On the other hand, growing competition between the agricultural sector and the higher economic value in urban and industrial uses of freshwater supplies make the reuse of wastewater a promising option to bring supply and demand into a better balance, particularly in arid and semi-arid regions(Winpenny et al., 2010).

The use of wastewater in agriculture combines these two aspects of wastewater and has increasingly been recognised as an effective, low-cost disposal method and a reliable alternative resource to conventional water resources especially in developing countries (Scott et al., 2004). It's water, and nutrient contents are important factors that combine to make it a valuable resource particularly in arid and semi-arid climates (Jiménez et al., 2010a).

Concern about the risks to human health and environment quality is a serious obstacle for wastewater reuse in agriculture. Three possible approaches can be used to deal with the risks of wastewater reuse in agriculture (Jiménez et al., 2010a) as shown in Figure 2-9 and outlined briefly below:

- An approach based on the traditional way of using wastewater treatment technologies (Figure 2-9a) aiming for health protection and the safeguarding of the environment. This approach requires advanced treatment in addition to conventional wastewater treatment to further improve water quality leading to very high costs and a reduction in the nutrient concentrations in the wastewater effluent(Jiménez et al., 2010a).
- An approach to use appropriate treatment alternatives (Figure 2-9b) to achieve adequate risk reduction and enhance the reuse of nutrients in addition to the water. Although this approach requires lower costs compared to the first option, the potential risks are solely controlled with treatment (Jiménez et al., 2010a).
- Finally, an integrated approach (Figure 2-9c) combining a local treatment process with non-treatment interventions and other risk reduction measures applied at different barriers from wastewater generation to the consumption of wastewater irrigated produce to ensure greater reduction in health and environmental risks (Jiménez et al., 2010a).

Achieving a sustainable and effective wastewater reuse project is quite complex, as it requires a comprehensive financial and economic analysis that considers all aspects of sustainability including health aspects, environmental and natural resources, technical feasibility, and the social-cultural and political aspects.

Furthermore, evaluating the economics of wastewater management options for mitigating environmental risks associated with the chemical constituents in the wastewater is a challenge due to many reasons including the fact that many environmental commodities have public good dimensions but do not have market values and may be difficult to quantify in monetary units. Also, there is a lack of implemented tools or models for assessing environmental risks and risk management approaches which can be used for economic analysis and justification for selecting management strategies under specific environment, socio-economic conditions. Additionally, in developing countries, the required analytical capacity for analysing specific pollutants (such as heavy metals and organic contaminants) is seldom adequate. Currently, there is a limited number of strategies for environmental risk reduction that have been economically assessed and proven to be cost effective (Molinos-Senante et al., 2011, Tziakis et al., 2009, Reymond et al., 2009, Bino et al., 2010, Wichelns et al., 2015) .

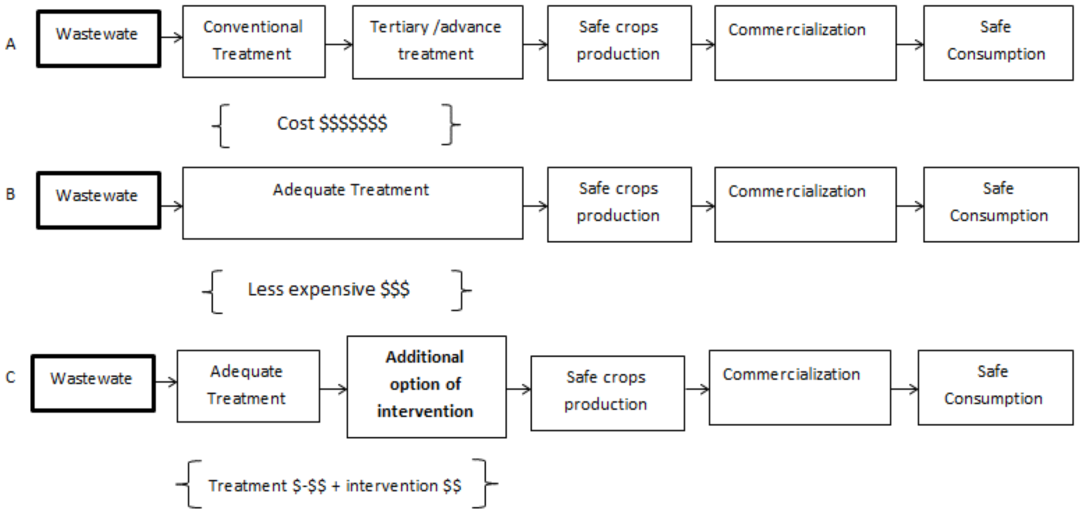


Figure 2-9 Options to deal with wastewater reuse in agriculture(Jiménez et al., 2010a)

Chapter 3. Water resource situation in Libya

3.1 Introduction

Libya is located in the north central part of Africa and covers a surface area of about 17,755,000 km^2 making it the fourth largest country in Africa (FAO, 2015). According to the World Bank, the Libyan population increased from about 4.5 million in 1993 to almost 6.3 million in (2015). About 75 to 80% of the population is settled in a strip of the Mediterranean coastline (about 1.5% of total territory) where the most fertile lands and major industrial projects are located (FAO, 2015, Wheida and Verhoeven, 2006)

The country is mostly arid; about 95% of the territory is desert, and only around 1.2% of the total land area is estimated to be cultivable (FAO, 2015, Wheida and Verhoeven, 2006). The Libyan climate is influenced by a semi-Mediterranean climate to the north coastal strip with a warm, relatively wet, winter and a dry, hot summer. The centre and south of the country, by contrast, has the Sahara desert climate with variation in temperature between winter and summer seasons from 0 to over 40°C (FAO, 2015, Salem, 2007, Wheida and Verhoeven, 2006).

Libya can be considered as one of the driest countries in the word with a share of renewable water per capita of less than 150 m^3 /day (Salem, 2007). Due to the low rainfall rate and almost the entire absence of surface water, the country relies heavily on groundwater for all its fresh water supply. As a result of the limited natural water resources and growing population and accompanying increased water demand, over the last few decades the country has started to experience a critical water shortage that threatens the country’s sustainable development and hinders agricultural and industrial activities.

3.2 Available water resources

3.2.1 Conventional water resources

As in any arid and semi-arid regions, the annual precipitation rate in Libya is extremely low with great variability in place and time. Figure 3-1 shows that more than 95% of the total surface land area receives less than 100mm of rainfall per year (FAO, 2015, Wheida and Verhoeven, 2007).

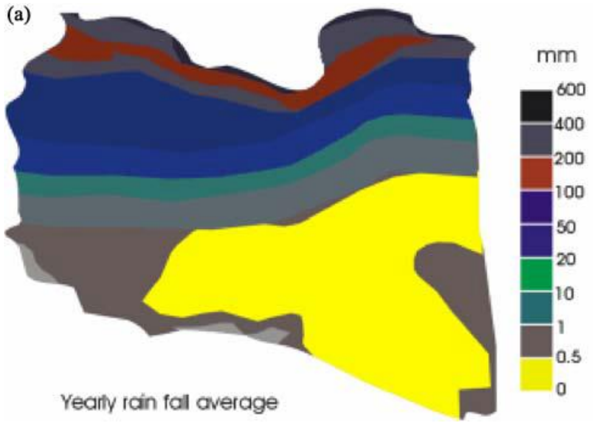


Figure 3-1 Average annual rainfall (Wheida and Verhoeven, 2007)

Due to the low average annual rainfall, the natural water resources in Libya are extremely limited. It has been estimated that the total annual amount of Libya's fresh water is 3820 million cubic meters. Surface water only accounts for about 170 million cubic meters while the amount of depletion of fossil groundwater represents 3000 million cubic metres/year (Eljadid, 2009, Aquil et al., 2012) Figure 3-2 illustrates the annual utilisation of fresh water.

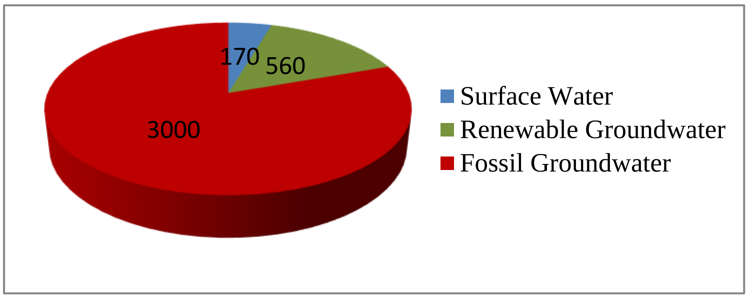


Figure 3-2 Annual utilise fresh water million m^3/year (Eljadid, 2009, Aquil et al., 2012)

Surface water ranges from scarce to absent, contributing about 2% of the total available water resource in Libya (Abufayed and Elkebir, 2010) due to the fact that the country has no lakes or perennial rivers. The total mean annual runoff is estimated to be between 200 million m^3 and 385 million m^3, the majority of it occurring in the northern areas of the country. However, a large proportion of the runoff, about 65 to 70% is lost through evaporation, while only 5-10% of it reaches the underlying aquifers (FAO, 2015, El Asswad, 1995)

Despite the consideration of surface water as a minor resource in the country, 16 storage dams have been constructed in different areas of the country with a total design storage capacity of 385 million m^3. However, the actual annual capacity of the existing dams is estimated to be only about 30-40 million m^3 (Wheida and Verhoeven, 2006, FAO, 2015). Also, around 29 springs of small to medium discharge capacity are scattered over different locations in the North East and North West of the country (highland areas) with a total outflow of 8667.6 l/s (FAO, 2015, Wheida and Verhoeven, 2006).

Groundwater is the most important water resource in the country constituting around 96.5% of the available water resources (Abufayed and Elkebir, 2010). It can be classified into renewable resources and non-renewable resources. Figure **3-3** shows the main reservoirs underlying the Libyan territory.

Figure 3-3the main groundwater basins in Libya (Wheida and Verhoeven, 2007)

Most of the renewable groundwater is contained in shallow aquifers located in the northern zones (Jabal Al akhder, Gefarah plain and Nafusah/al Hamada). These depend on rain events and surface runoff for their recharge. The average annual recharge is around 250 million m^3(Wheida and Verhoeven, 2007, Abufayed and Elkebir, 2010). Currently the water demand for all sectors, particularly agriculture is rising as a consequence of economic and population growth along the coastal strip. This has led to severe depletion of water resources and water quality deterioration in most of these aquifers (Wheida and Verhoeven, 2006, FAO, 2015, El Asswad, 1995)

Non-renewable groundwater is fossil water located in deep aquifers in the central and southern parts of the country, specifically in the Murzuq, Kufirah and As- Sarir basins. This water is of a good quality with total dissolved solids below 1500 mg/l (Wheida and Verhoeven, 2007, Aquil et al., 2012). Table 3.1 provides a summary of the characteristics of the main groundwater aquifers in Libya.

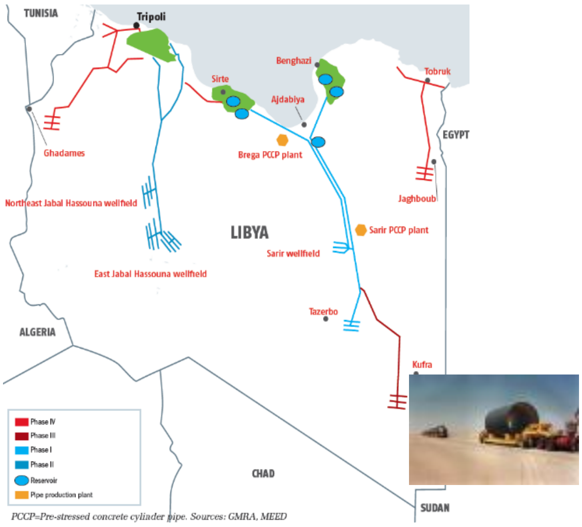
Table 3-1 Groundwater aquifers characteristics (Wheida and Verhoeven 2007; Aquil, Tidall and Moram 2012)

Basin characteristics	Usable water		Total dissolved solid mg/l
	Renewable in million m^3/y	Non- Renewable million m^3/y	
Jabal Al akhder	200	50	1000-5000
Gefarah plain	200	50	1000-5000
Nafusah/al Hamada	250	150	1000-5000
Fazzan or Murzuq	-	1800	200-1500
Kufirah/ As- Sarir	-	1800	200-1500

Over the last three decades the Libyan Government has responded to the increase in water scarcity in the northern part of the country by exploiting these non-renewable groundwater sources. It has primarily been achieved through the Manmade River (MMR) project, a major infrastructure investment designed to withdraw and transfer fossil water from the desert to the Mediterranean strip where most of the population lives (FAO, 2015, Eljadid, 2009, Wheida and Verhoeven, 2007).

The project was started in 1984 through to completion in 2010 and the Libyan government has spent more than \$20bn on the project. Prior to the conflict in 2011 the plan aimed to eventually transfer 6 million m^3/year of fossil water to supply all the Northern regions by 2030 for different water demands (MEEDinsight, 2012). The project consists of four phases as shown in Figure 3-4 and Table 3-2. The first phase covers the Kufra-Tazerbo- Sarir-Ajdabiya-Sirte-Benghazi systems in the east of the country, second phase takes in the Hassouna- Tripoli-Tarhouna network west of the country, while phase three involves the construction of pumping stations at the Kufra wellfield and pipeline to linking the field with the Sarir/Tazerbo network (phase one), finally phase four covers the Jaghboub- Tobruk system and Ghadames-Azzawiya-Zuara system (MEEDinsight, 2012).

In 1993, the Libyan authority issued an order to utilize around 80% of the water conveyed by the manmade river for agriculture purposes with the aim of being a self sufficient country. Of the rest, 12% and 5% for supplied for municipal and industrial purposes respectively while 3% is predicted to be lost during the conveyance process due to leakge (Wheida and Verhoeven, 2007, Aquil et al., 2012) Table 3-3 provide a summary of planned water usage per sector for the first three phases of the project. To date, only the first two phases of the project have been implemented and now convey more than 2 million m^3/day to various demand sites in the north of the country (Aquil et al., 2012).



PCCP=Pre-stressed concrete cylinder pipe. Sources: GMRA, MEED

Figure 3-4 Man- Made River Project (MEEDinsight, 2012)

Table 3-2 Man-Mad Rivers Phases (FAO 2015; Eljadid 2009; Wheida and Verhoeven 2007; MEEDinsight 2012)

Phase No.	Location	Design capacity Million m^3/year	Capital investment In million $ US	Note
Phase I	Sarir-Sirt-Tazerbo-Benghazi	2	3800	- about 80% of water are planned for agriculture activates
Phase II	Hasouna- Gfara plain	2.5	7220	- Currently, only 2 Millionm^3/day is conveyed to different demand areas. - Around 70% of conveyed water planned for agriculture purposes.
Phase III	Kufra-Tazerpo	1.68	2460	- Under construction
Phase IV	Ghadames- Zwara	0.249	960	- Under construction - Understudy
	Gaghboub- tobruck	0.137	-	

Table 3-3 Planned water usage for the first three phases of the Man-Made River Project (m3/day) (MEEDinsight 2012)

Phase No.	Municipal	Agricultural	Industrial	Total in million
Phase I	410,170	1,506,030	83,800	2
Phase II	1316090	1,175,660	8,250	2.5
Phase III	253,000	1,427,000	0	1.68

3.2.2 Non-conventional water resources

As previously mentioned, the Libyan Government has responded to the issue of water scarcity predominantly through utilising fossil groundwater, with only a minor emphasis on integrating non-conventional water resources such as seawater desalination and wastewater reuse into national water resources management (Figure 3-5).

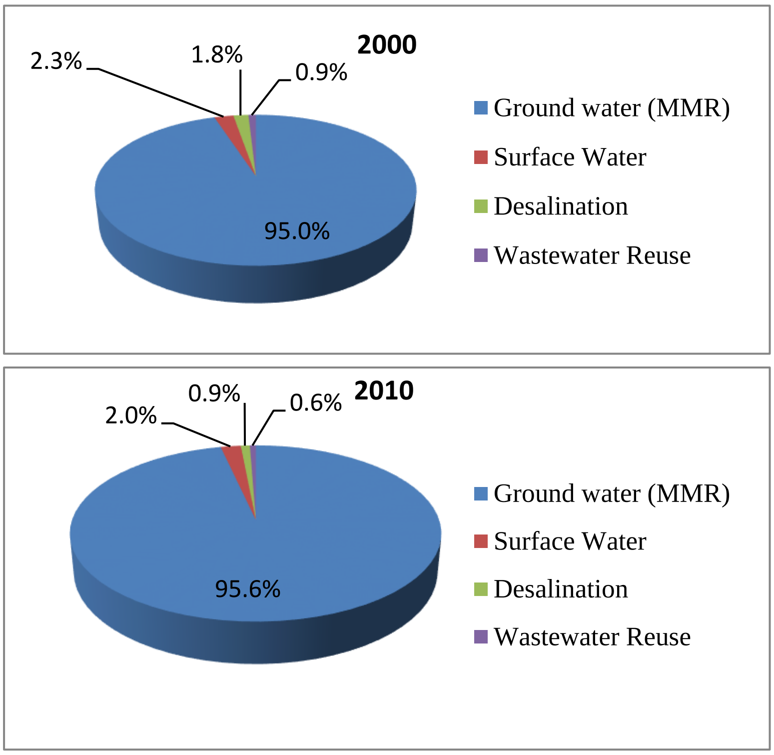
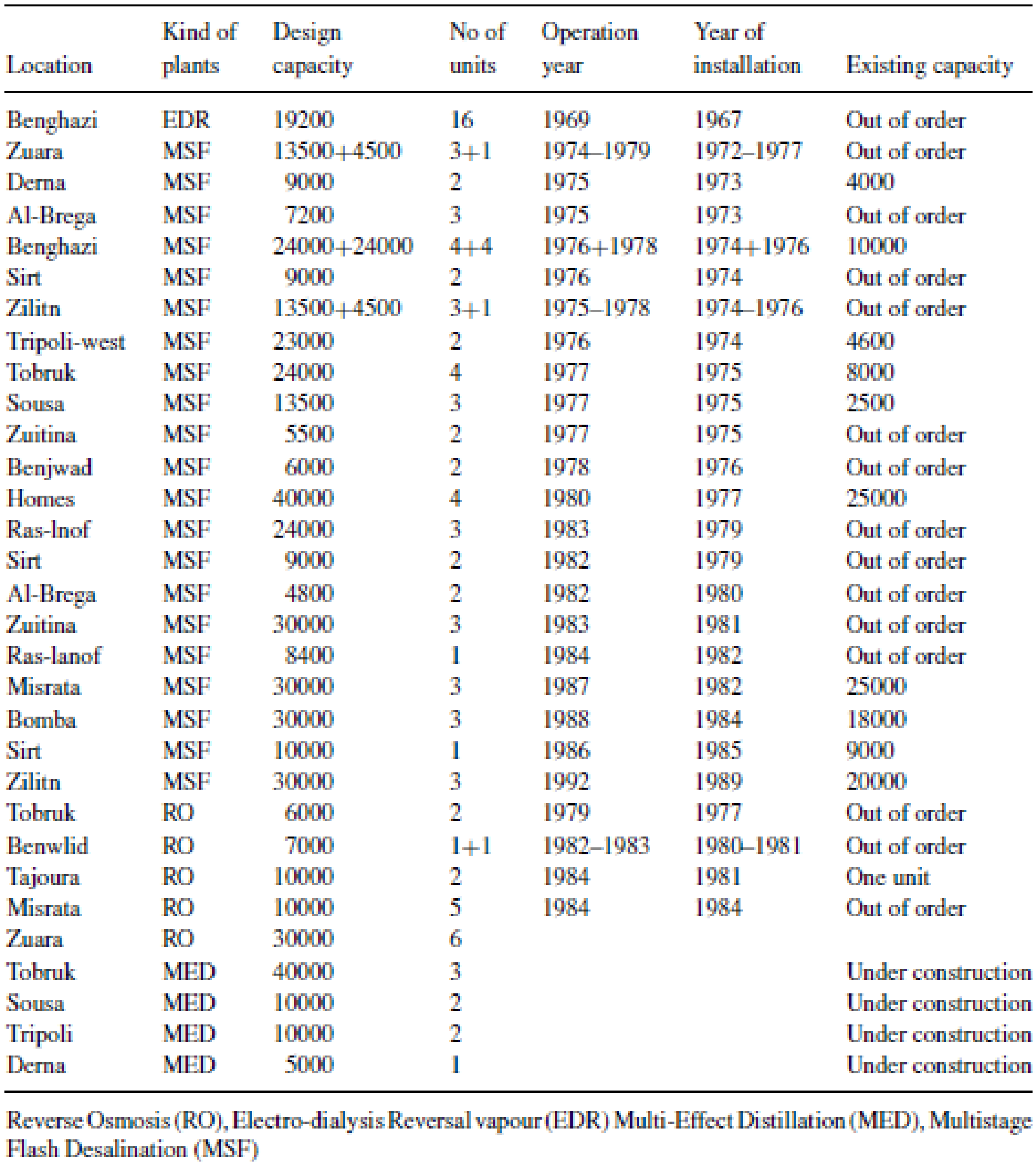


Figure 3-5 Available water resources in Libya (FAO 2015; Abufayed and Elkebir 2010)

Nevertheless, several attempts have been made over the past five decades to install seawater desalination and also to promote the reuse of treated wastewater. A number of desalination plants have been constructed in major coastal cities and industrial complexes with a total capacity of about 65 million m^3/ year. However, due to the restrictions imposed by limited financial resources (as they have not been given priority by the government) and a lack of spare parts, the actual operating capacity is estimated to have decreased to 30 million m^3/ year in the last few years (Wheida and Verhoeven, 2007). Table 3-4 summarizes the characteristics of the installed desalination plants in Libya. The contribution of existing desalination plants in 2010 were estimated to be less than 2% of the total water supply and used exclusively for municipal and industrial purposes (Abufayed and Elkebir, 2010).

Table 3-4 Overview of the medium and large size desalination plants (Wheida and Verhoeven 2007; Aquil, Tidall and Moram 2012)

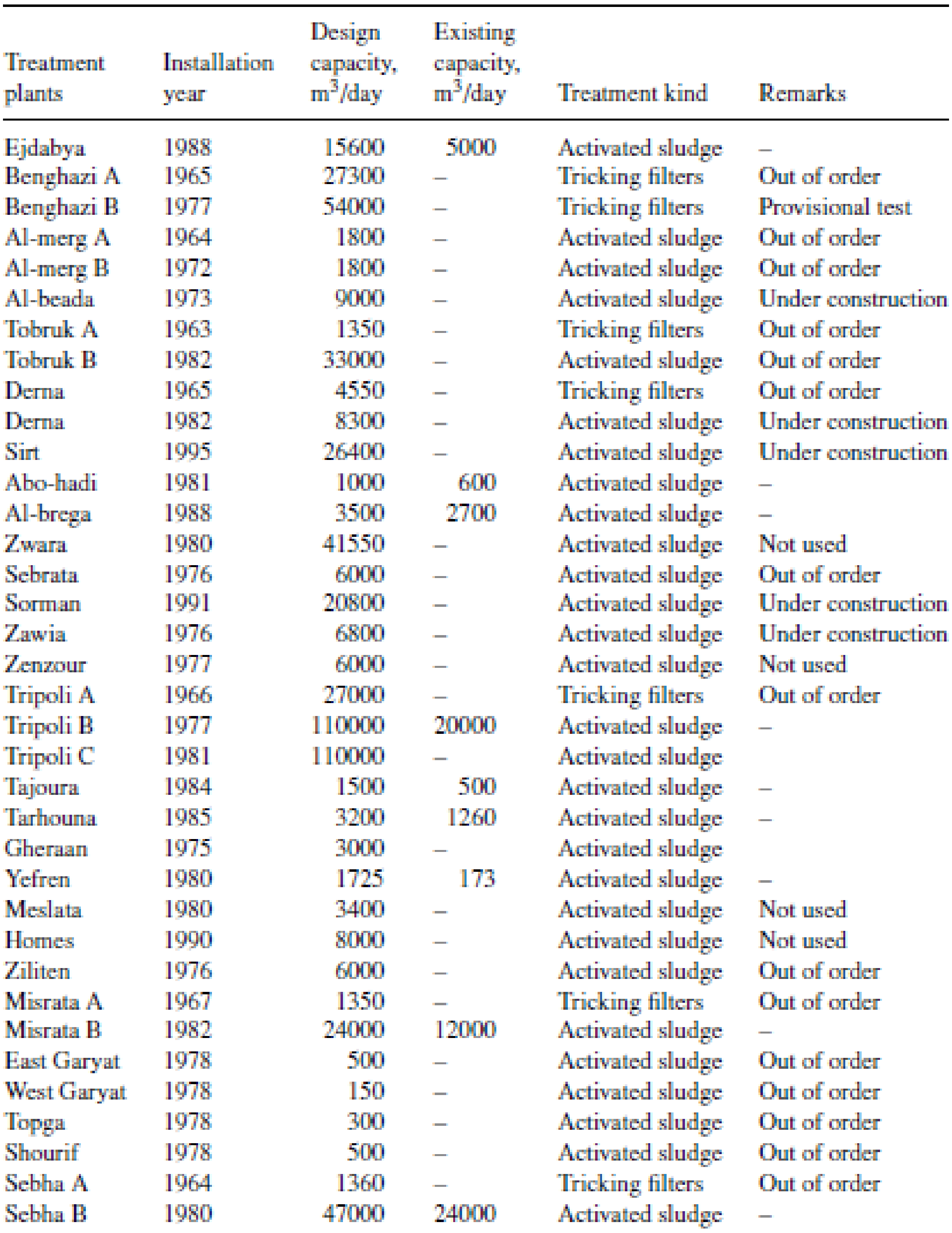


Location	Kind of plants	Design capacity	No of units	Operation year	Year of installation	Existing capacity
Benghazi	EDR	19200	16	1969	1967	Out of order
Zuara	MSF	13500+4500	3+1	1974–1979	1972–1977	Out of order
Derna	MSF	9000	2	1975	1973	4000
Al-Brega	MSF	7200	3	1975	1973	Out of order
Benghazi	MSF	24000+24000	4+4	1976+1978	1974+1976	10000
Sirt	MSF	9000	2	1976	1974	Out of order
Zilitn	MSF	13500+4500	3+1	1975–1978	1974–1976	Out of order
Tripoli-west	MSF	23000	2	1976	1974	4600
Tobruk	MSF	24000	4	1977	1975	8000
Sousa	MSF	13500	3	1977	1975	2500
Zuitina	MSF	5500	2	1977	1975	Out of order
Benjwad	MSF	6000	2	1978	1976	Out of order
Homes	MSF	40000	4	1980	1977	25000
Ras-lnof	MSF	24000	3	1983	1979	Out of order
Sirt	MSF	9000	2	1982	1979	Out of order
Al-Brega	MSF	4800	2	1982	1980	Out of order
Zuitina	MSF	30000	3	1983	1981	Out of order
Ras-lanof	MSF	8400	1	1984	1982	Out of order
Misrata	MSF	30000	3	1987	1982	25000
Bomba	MSF	30000	3	1988	1984	18000
Sirt	MSF	10000	1	1986	1985	9000
Zilitn	MSF	30000	3	1992	1989	20000
Tobruk	RO	6000	2	1979	1977	Out of order
Benwlid	RO	7000	1+1	1982–1983	1980–1981	Out of order
Tajoura	RO	10000	2	1984	1981	One unit
Misrata	RO	10000	5	1984	1984	Out of order
Zuara	RO	30000	6			
Tobruk	MED	40000	3			Under construction
Sousa	MED	10000	2			Under construction
Tripoli	MED	10000	2			Under construction
Derna	MED	5000	1			Under construction

Reverse Osmosis (RO), Electro-dialysis Reversal vapour (EDR) Multi-Effect Distillation (MED), Multistage Flash Desalination (MSF)

Wastewater treatment facilities were established in Libya as early as the middle of the 1960s mainly to protect public health and reduce environmental pollution. The objective was also to develop additional non-conventional water sources and as a result most of these plants were designed to treat wastewater for agricultural purposes (Wheida and Verhoeven, 2007). Currently, most of the wastewater treatment plants are either inefficient or out of order as is shown in Table 3-5 (Aquil et al., 2012). The total volume of the available treated wastewater represents only a minor contribution to the total water supply, and it is used exclusively for animal fodder irrigation (Eljadid, 2009, Abufayed and Elkebir, 2010).

Table 3-5 Overview of the wastewater treatment plants (Wheida and Verhoeven 2007; Aquil, Tidall and Moram 2012)



Treatment plants	Installation year	Design capacity, m^3/day	Existing capacity, m^3/day	Treatment kind	Remarks
Ejdabya	1988	15600	5000	Activated sludge	–
Benghazi A	1965	27300	–	Tricking filters	Out of order
Benghazi B	1977	54000	–	Tricking filters	Provisional test
Al-merg A	1964	1800	–	Activated sludge	Out of order
Al-merg B	1972	1800	–	Activated sludge	Out of order
Al-beada	1973	9000	–	Activated sludge	Under construction
Tobruk A	1963	1350	–	Tricking filters	Out of order
Tobruk B	1982	33000	–	Activated sludge	Out of order
Derna	1965	4550	–	Tricking filters	Out of order
Derna	1982	8300	–	Activated sludge	Under construction
Sirt	1995	26400	–	Activated sludge	Under construction
Abo-hadi	1981	1000	600	Activated sludge	–
Al-brega	1988	3500	2700	Activated sludge	–
Zwara	1980	41550	–	Activated sludge	Not used
Sebrata	1976	6000	–	Activated sludge	Out of order
Sorman	1991	20800	–	Activated sludge	Under construction
Zawia	1976	6800	–	Activated sludge	Under construction
Zenzour	1977	6000	–	Activated sludge	Not used
Tripoli A	1966	27000	–	Tricking filters	Out of order
Tripoli B	1977	110000	20000	Activated sludge	–
Tripoli C	1981	110000	–	Activated sludge	
Tajoura	1984	1500	500	Activated sludge	–
Tarhouna	1985	3200	1260	Activated sludge	–
Gheraan	1975	3000	–	Activated sludge	
Yefren	1980	1725	173	Activated sludge	–
Meslata	1980	3400	–	Activated sludge	Not used
Homes	1990	8000	–	Activated sludge	Not used
Ziliten	1976	6000	–	Activated sludge	Out of order
Misrata A	1967	1350	–	Tricking filters	Out of order
Misrata B	1982	24000	12000	Activated sludge	–
East Garyat	1978	500	–	Activated sludge	Out of order
West Garyat	1978	150	–	Activated sludge	Out of order
Topga	1978	300	–	Activated sludge	Out of order
Shourif	1978	500	–	Activated sludge	Out of order
Sebha A	1964	1360	–	Tricking filters	Out of order
Sebha B	1980	47000	24000	Activated sludge	–

3.3 Water Supply and use

Three major events have influenced water use in Libya over the last 40 years. Firstly the increase in demand for water supply at a time when groundwater quality and availability was deteriorating in coastal areas. Secondly the commencement of the Manmade River project to transport water to different areas in the coastal strip. Finally, the rapid development of private agriculture (Wheida and Verhoeven, 2006). Figure 3-6 summarises water consumption by sector in Libya.

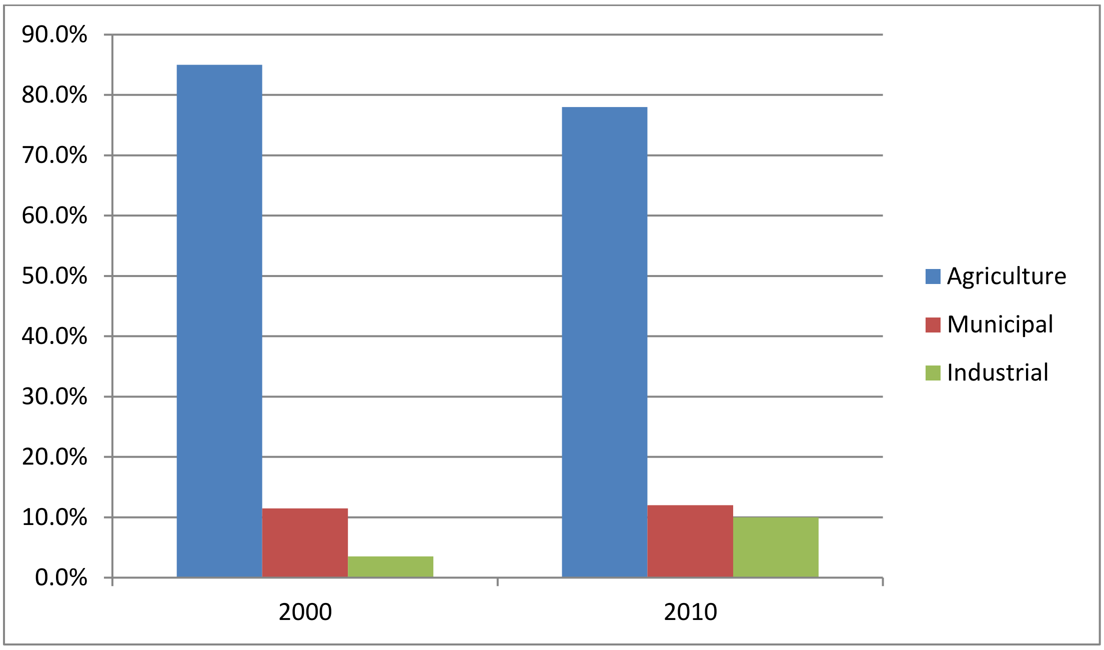


Figure 3-6: Water Consumption by Sectors (Wheida and Verhoeven 2006; Aquil, Tidall and Moram 2012)

Municipal water demand has increased considerably in response to a growing population and increased per capita requirements. Average water consumption per capita is estimated to be quite high from 200 L/day to 350 L/day and in some areas might exceed 450 L/day. The consumption rate per capita is high partly due to the widespread use of water for non-essential purposes such as gardening, especially in the summer and the absence of water metering (which also means that accurate information on water usage is scarce). The high rates of leakage in water networks may also be a factor contributing to the high per capita rates of usage (Abufayed and Elkebir, 2010, Wheida and Verhoeven, 2006). Practically, all municipal water usage relies primarily on groundwater sources. Around 95% of these supplies comes from the MMR project while desalinated water contributes only about5% of municipal supplies. Use of rainwater harvesting and private wells has also been practiced especially in non-urban areas. However, its contribution to the overall municipal water supply is minor (Wheida and Verhoeven, 2006, Abufayed and Elkebir, 2010).

In general, industrial activities are limited all over the country with the lowest portion of total water consumption. Most of the water consumption in the industrial sector occurs in the oil production fields, and this depends heavily on groundwater supplies (Wheida and Verhoeven, 2006, Eljadid, 2009).

Due to the adoption of a self-sufficiency policy in terms of food and a lack of monitoring or pricing of informal water use, development of agricultural activities has grown enormously. In the last 20 years, private irrigation has been rapidly increasing and it is estimated that 81.3%

of irrigated areas are privately irrigated while 18.7% use state-managed irrigation (Wheida and Verhoeven, 2007, FAO, 2015). From Figure 3-6 it is clear that agriculture is the highest water consuming sector in the country with approximately 80% of all the water supplied utilised in agriculture. It has been reported that around 80% of agricultural production relies on irrigation (FAO, 2015). About 99% of irrigation water is estimated to be from groundwater while treated wastewater and surface water only contribute 1% (FAO, 2015). In 2000 about 47% of total renewable groundwater abstraction in the northern part of the country was used for private irrigation representing the main sector of renewable groundwater consumption (FAO, 2015). However, due to renewable groundwater deterioration in coastal areas due to saline intrusion, the country has put a target to meet all agriculture demands in these areas mainly from the man-made river.

3.4 Current Water Resource Situation

Libya started facing a water deficit from the middle of the 1990s and this was felt mainly in the agricultural and municipal sectors. Despite the vigorous efforts made by the country, this deficit is estimated to rise from 1153 million m^3 to around 6000 million m^3 in 2025 due to the rapidly increasing water demand for all sectors especially agriculture beyond the limits of the available water resources (FAO, 2015, Wheida and Verhoeven, 2006, Abufayed and Elkebir, 2010). Figure 3 7 the increase of water deficits since 1998(FAO, 2015, Wheida and Verhoeven, 2006, Abufayed and Elkebir, 2010)

Groundwater abstraction, especially in the northern part of the country, has been exceeding the natural recharge for many years and this has resulted in a significantly decline in groundwater levels in many coastal areas (El Asswad, 1995, Wheida and Verhoeven, 2004). It has been forecasted that the water from certain aquifers might be depleted in the next few years (El Asswad, 1995). As a result of over-exploitation of renewable groundwater, saline seawater intrusion has also become a serious problem causing a deterioration in the quality of many coastal groundwater resources (El Asswad 1995) It has been reported that salinity levels have been increasing at the rate of 15-20 ppm/y (El Asswad, 1995) and this has made many of the aquifers unusable because of their high salinity. In the last few decades, different studies of seawater intrusion around Tripoli indicated that the rate of seawater intrusion into land ranges from 50 to 550 m/yr. Figure 3-7 shows the seawater intrusion around Tripoli from 1957-1995 (Salem, 2005).

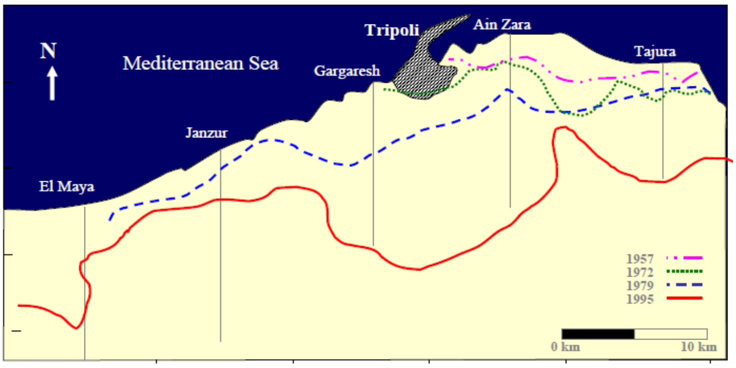


Figure 3-7: Seawater Intrusion Evolution (Salem 2005)

Transporting fossil water from the desert to the coastal region using the manmade river is a successful short-time solution for overcoming the current water shortage and water deterioration in those areas. However, as a result of adopting a self-sufficiency policy in food, an expansion of the irrigated areas and over irrigation practices, fossil groundwater has been over-exploitation causing more depletion of water resources (Wheida and Verhoeven, 2007). Since most of the country's groundwater resources are non-renewable, it would be impossible in future to meet all the water demand for obvious reasons including the high cost, non-renewable nature of the resource (and hence its finite availability) and the possibility of quality deterioration over time (Wheida and Verhoeven, 2007). Continuing the present pattern of utilising limited water resources will eventually lead to more strain on its availability and cause significant impacts on society, the economy and the environment.

3.5 Need for integrated water resource management

Libya is facing a severe water crisis and is one of the driest countries in the world. The renewable water use per capital decreased from around 325m^3/year in 1972 to less than 111 m^3/year in 2014 (FAO-AQUASTAT, 2015), and it is estimated to reach 70 m^3/year by 2025 (Abufayed and Elkebir, 2010). With low rainfall and the absence of reliable surface water sources, the country has increasingly relied on groundwater resources for all supplies. Currently, water demand dramatically exceeds the conventional water resources capacities resulting in serious depletion and water quality deterioration as well as socioeconomic and environmental consequences.

In addition, to the scarcity of water resources, malpractices in water management have taken their toll on the water resources available in Libya. This includes the low price of freshwater delivered to consumers that does not reflect its scarcity or does not recover the cost of supply. In addition there is a lack of charge for or control over groundwater abstractions particularly for the agriculture sector, contributing to accelerating water shortage problems. By continuing down this path, water resource availability may become a rate-limiting factor in the country’s development and therefore this calls for sustainable and integrated water resource management to minimise the impact of the current and future water crises (Wheida and Verhoeven, 2007).

One of the keys to sustainable management of water resources would be the development of integrated strategies that allocate available water efficiently to meet social, economic and environmental demands, and eliminate the unfair priorities that lead to low reliability in water supply among other users (Feng, 2001). Figure 3-6 shows that agriculture has by far the largest portion of water consumption in the country and it may be considered as the major factor driving water shortages in the country (Wheida and Verhoeven, 2007). In the absence of legal or financial incentives, agriculture is likely to be a highly inefficient user of the resource. While irrigation utilises about 80% of water supply, the economic contribution from agriculture has been insignificant over the last three decades at less than 10% of the country income (Wheida and Verhoeven, 2007). Therefore, the consideration of reallocation of water from the agricultural sector to satisfy more economically important water users is an essential step for sustainable water resource management. In this situation, wastewater may provide a reliable source of irrigation water and enable freshwater to be utilised for more economically valuable purposes.

Chapter 4. Methodology used for the development of the evaluation tool

4.1 Introduction

Growing competition between the agricultural and the higher economic value in urban and industrial uses of high-quality freshwater supplies, especially in regions where water scarcity is a major problem, will increase the pressure on this precious resource. Under these circumstances, wastewater may provide a reliable source of irrigation water for agriculture and enable freshwater to be utilised for more economically valuable purposes.

Concern regarding the risks from the microbial and toxic components in the wastewater, to human health and environmental quality is a serious obstacle for wastewater reuse, particularly in agriculture. Although powerful approaches and tools for microbial risk assessment and management for safe use of wastewater are now available, there is still a lack of a systematic analytical approach for evaluating wastewater management options for mitigating the environmental risks associated with the chemical constituents in the wastewater which can be used for economic analysis and justification under specific environment, social and economic conditions In seeking a pragmatic solution towards more sustainable wastewater reuse, there remains a need for research incorporating both health and environmental risk assessment and management with economic and financial analysis to combine quantitatively cost, benefits, and risks and to rank alternative reuse options.

To optimise the trade-offs between prevention of the risks to public health and the environment and to preserve the substantial benefits, an integrated approach combining health risk assessment, environmental risk assessment, and a cost-benefit analysis was applied in this study to estimate the health and environmental risks and attempts to assign a monetary value to the costs and benefits of alternative strategies for wastewater reuse in agriculture. Figure 4-2 shows the conceptual framework, which is representative of the elements and criteria that have been used to develop the tool. This research was based on data from a case study that provided a real-world context for the verification and validation of the approach. A case study in Misurata in Libya was chosen for this purpose. The reason for choosing this area is that the farmers rely heavily on the use of groundwater for irrigation and currently there is a lack of any strategy for reusing wastewater in agriculture. This chapter provides a summary of the research methodology for developing the evaluation approach. More details on methods and results are provided in chapters 5, 6 and 7.

4.2 Risk assessment methodology

Both health and environmental risk assessments were carried to evaluate the potential consequences of reusing wastewater for irrigation. Chapters 5 and 6 explain in more detail the specific methods and approaches for assessing the health and environmental risks from wastewater irrigation respectively.

4.2.1 Health Risk Assessment

Quantitative Microbial Risk Assessment and the Monte Carlo computer program MC-QMRA was used for assessing health risks associated with wastewater reuse in agriculture. Figure 4-1 illustrates the approach for quantitative health risk assessment.

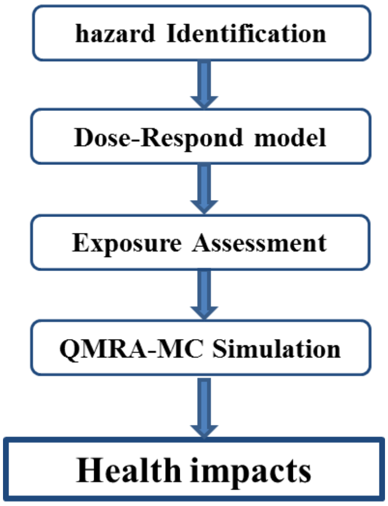


Figure 4-1 Quantitative health risk assessment

4.2.1.1 Hazard Identification

In order to apply QMRA, it is essential to identify the causative pathogens (pathogenic indicators) of acute and chronic human health effects. Four “key” pathogens were selected: Norovirus (a viral pathogen), Salmonella (a bacterial pathogen), giardia (a protozoan), and Ascaris (a helminth pathogen). These pathogens have been chosen based on a review of literature regarding the epidemiological investigations of the prevalent diseases and the history of disease outbreaks from Libya, the Middle East and North Africa (the review is provided in Annex 3).

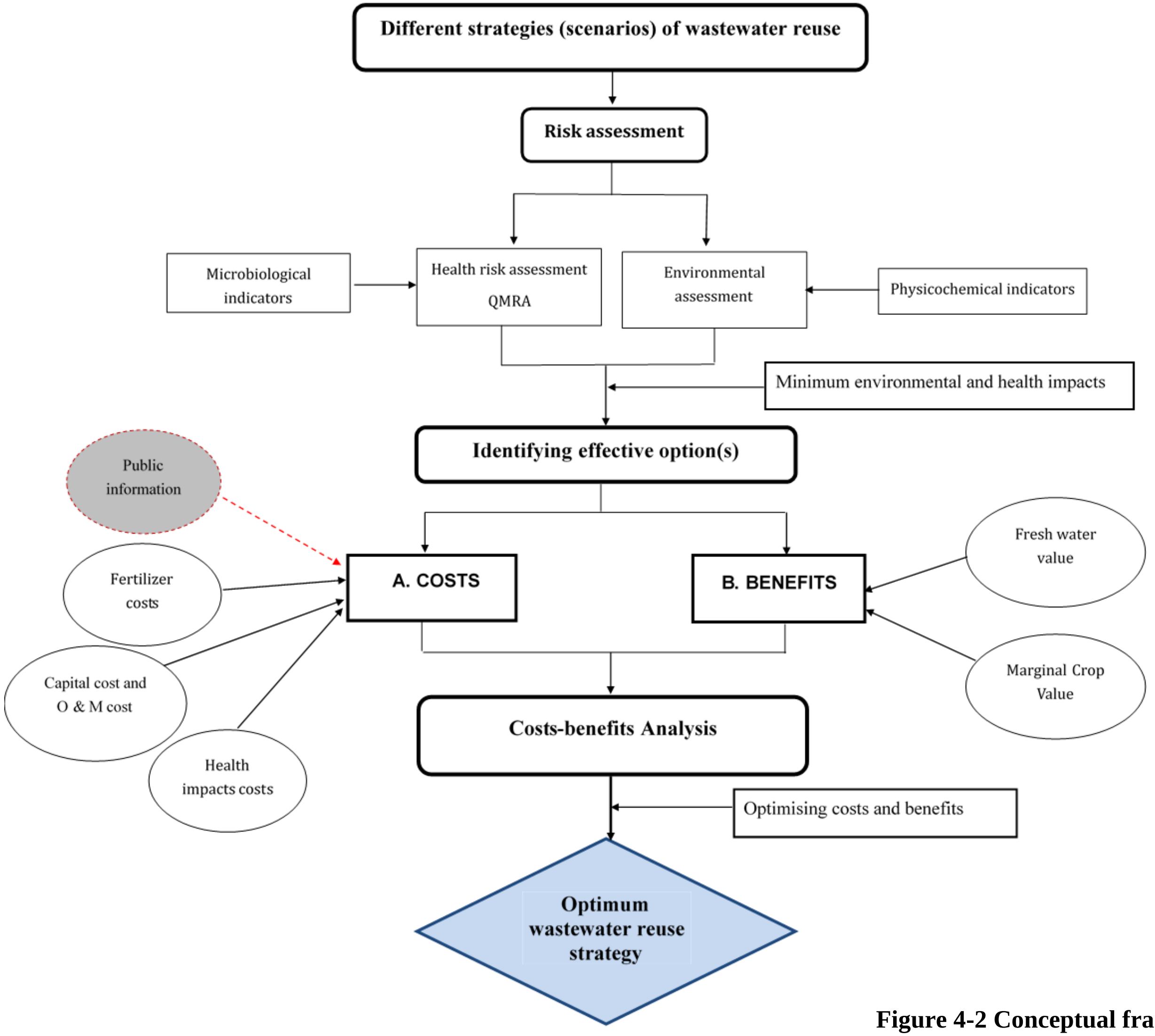


Figure 4-2 Conceptual framework

4.2.1.2 Dose-response model

The quality of the QMRA analysis depends largely on the availability of dose-response information (characterizing the relationship between a range of doses administered and the incidence of health impacts). Dose–response models were available in the literature for the key pathogens. The ß-poison dose- response model was used to estimate the risk of Norovirus, *Salmonella* and Ascaris infections (Haas et al., 1999, Teunis et al., 2008, Mara and Sleigh, 2010c) while the exponential model was used for *Giardia* infection (Rose et al., 1991). The equations for these two models are shown below.

$$\mathbf{P_I(d) = 1 - e^{(-rd)}}$$ (Exponential dose-response model) Equation 4-1

$$\mathbf{P_I(d) = 1 - [1 + \left({}^{d}/_{N_{50}}\right)\left(2^{1/\alpha} - 1\right)]^{-\alpha}}$$ (Beta-Poisson dose–response model) Equation 4-2

4.2.1.3 Exposure Assessment

Exposure assessment includes determining the exposure routes, the duration and frequency of exposure, and the population exposed to the wastewater. Two exposure scenarios were assessed in this study to determine the health impacts from wastewater irrigation. These scenarios were:

1. **Restricted irrigation** (Farmers' exposure scenario), this includes irrigation of fodder crops, grains, and trees
2. **Unrestricted irrigation** (Consumers' exposure scenario), irrigation all type of crops including salad crops and vegetable that may be eaten uncooked.

4.2.1.4 QMRA-MC Simulation and health impacts

Monte Carlo - Quantitative Microbial Risk (MC-QMRA) simulation programmes based on the improved Karavarsamis-Hamilton method[1] were used to estimate the annual median risks of pathogen infections at 10,000 iterations over a varied range of wastewater qualities under selected exposure scenarios. Based on the results of the MC-QMRA simulation, alternative wastewater reuse strategies (Figure 4-3) were assessed to estimate their associated health impacts in terms of DALYs. Figure 4-4 shows the method by which health impacts have been estimated.

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[1] Simulations using QMRA: A Beginners Guide - Monte carlo simulation programmes, (the program is available at: http://www.personal.leeds.ac.uk/~cen6ddm/QMRAbeginners.html)

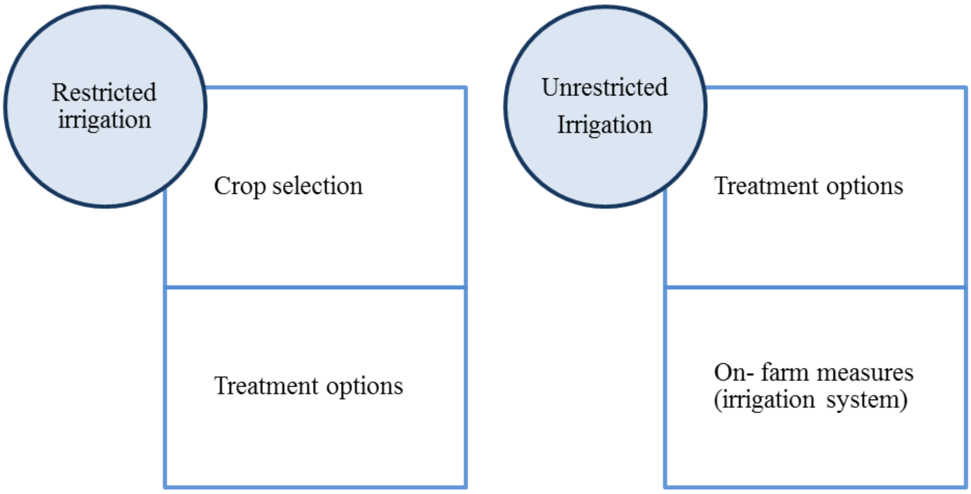


Figure 4-3 Wastewater reuse strategies

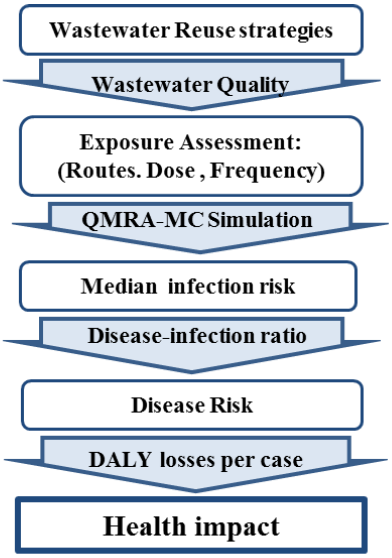


Figure 4-4 Estimating Health Impacts from alternative wastewater reuse strategies

Estimating health impacts requires selecting a tolerable maximum additional burden of disease expressed in DALY. In addition, the disease burden expressed as DALY loss per case of disease and the disease infection ratios must also be known or estimated.

Following the publication of the Update to the WHO 2006 Guidelines, a maximum tolerable additional DALY loss of 10^{-4} per person per year was selected and used in this study (Mara et al., 2010b). Using a tolerable additional DALY loss of 10^{-4} would be more practical and cost effective.

The disease burden expressed as DALY loss per case of diseases for Norovirus, Salmonella and Giardia were adopted from the WHO Estimates of the Foodborne Disease Burden in 2010 in the Eastern Mediterranean Region (EMR) (Torgerson et al., 2015, Kirk et al., 2015), while the DALY loss per case of Ascaris was estimated based on the information given by (Havelaar and Melse, 2003).

4.2.2 Environmental Risk Assessment

The environmental risks arising from reuse of wastewater are more complicated and difficult to evaluate and quantify particularly because it often involves ethical and moral concerns that could be unrelated to their economic value or use. In addition, the quality of the information gained from the assessment of the chemical impacts from reusing wastewater varies considerably between different chemical hazards.

Since neither the methodology nor any computer-based tools that can be used to assign a value to environmental risks are currently available primarily due to the fact that so many variables and constraints need to be considered, quantifying these risks in terms of a monetary value is much more challenging. Figure 4-5 describes the methodology by which the potential environmental risks and risk management options were assessed. Chapter 6 presents full details regarding the methodology for the environmental risk assessment.

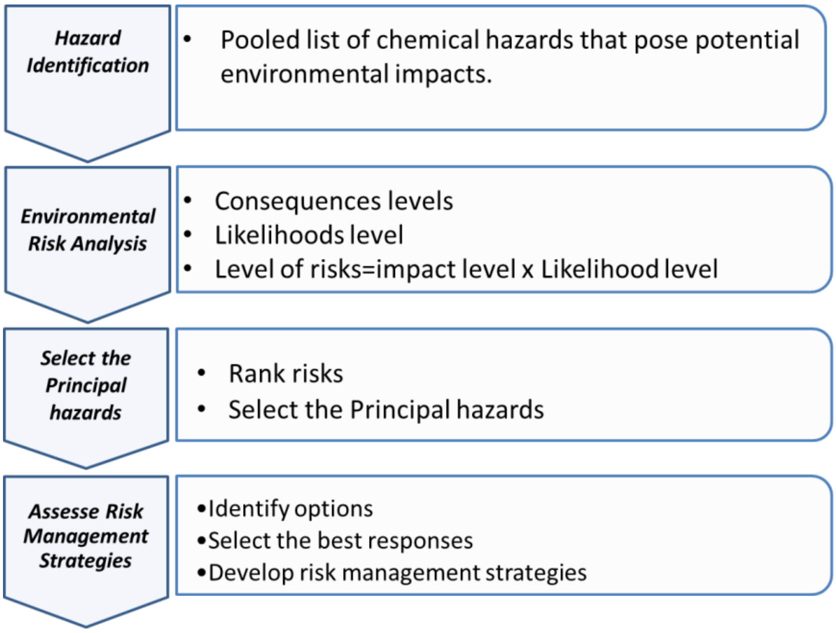


Figure 4-5: Environmental Risk Assessment

4.2.2.1 Hazard Identification

From the literature review presented in Chapter 2 it is clear that wastewater contains various types and concentrations of contaminants depending on its source and the degree of treatment. Generally, the most critical water quality problems in relation to environmental risks from wastewater reuse for irrigation are excessive levels of salt, heavy metals, excessive nutrients, toxic organic compounds and emerging contaminants.

4.2.2.2 Environmental Risk analysis

Relative environmental risk assessment was carried out to evaluate and rank the environmental risks associated with the use of wastewater contaminated with various chemical pollutants in the arid and semi-arid environment. The significance of any risk is a function of both the likelihood of hazards being realised and a measure of the consequences of the hazard should it happen. In its simplest form this can be illustrated as follows

Risk = A function of (Consequence and Likelihood) - In this research the level of risk from an identified hazard was calculated based on a formal judgement on the consequence and probability using a simple mathematical form of:

Risk = Impact Level x Likelihood Level - The key element for any valid risk assessment is to establish procedures for determining consequences (the impacts) and the likelihood (the probability of the hazard been realised) levels of each set of contaminants occurring under any environmental conditions as a result of irrigation with wastewater. For qualitative assessment, adequate descriptions for each level of consequences and likelihood is required.

Describing a potential impact involves an evaluation of its characteristics, together with the attributes of the receiving environment. Relevant impact characteristics could include:

- Whether the impact is direct or indirect;
- Whether there is impairment of ecosystem functions
- Whether the impact is long, medium or short- term impacts
- Whether there is a cumulative impact (A cumulative impact is "*the impact on the environment which results from the incremental impact of the action when added to other past, present and reasonably foreseeable future actions*"(Eccleston, 2011).

The Table 4-1 shows a qualitative consequence table that was be used to scale the environmental impacts as a result of irrigation with wastewater. In the table, it can be seen that impacts can range from very low (no obvious and direct impact, score of 1) to high (direct and irreversible score of 4).

Table 4-1: Consequences scale derived from(standards Australia, 2004a, 2004b)

Impact Level	Score	Description
High	4	Direct impacts, long-term or irreversible impacts with impairment of ecosystem functions
Medium	3	Medium term environmental impacts
Low	2	Minor impacts on biological of physical environment and not affecting ecosystem functions
Negligible	1	No obvious and direct impact

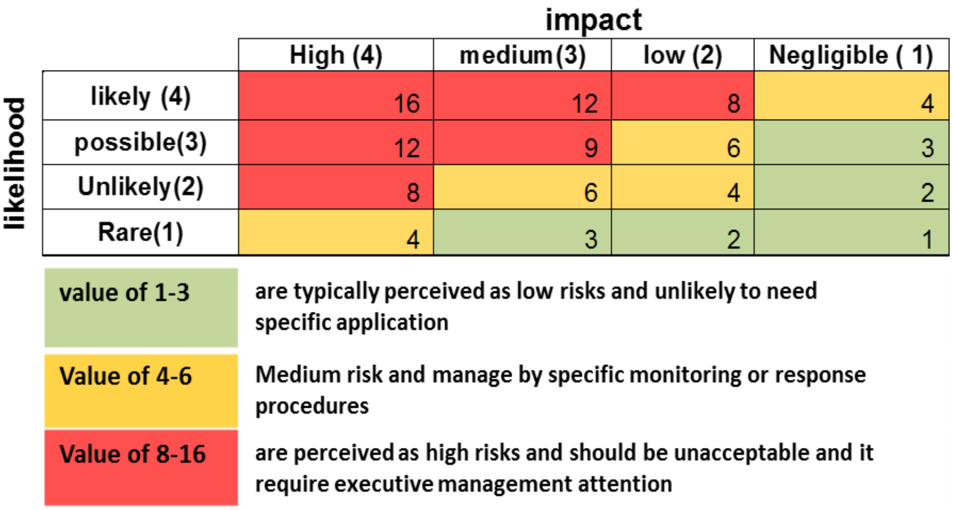
The qualitative likelihood also has four levels ranging from Rare (Lack of evidence but not impossible with a score of 1); to likely (expected to occur; with a score of 4) (Table 4-2) (standards Australia, 2004a, 2004b).

Table 4-2 Likelihood definitions derived from(standards Australia, 2004a, 2004b)

Level	Score	Description
Likely	4	It is expected to occur
Possible	3	May occur sometimes
Unlikely	2	Uncommon but has been known to occur
Rare	1	Lake of evidence but not impossible

4.2.2.3 Select principal hazard

A simple risk matrix was used to evaluate and then rank the risks as illustrated in Figure 4-6 where the risk level of 1-3 (green) are typically perceived as low risks and can be accepted, and a level of 4-6 (orange) medium risk and managed by specific monitoring or response procedures, while risk a level of 8-16 (red) are perceived as high risks and should be unacceptable and it is important to manage these risks. For simplicity, only the highly ranked hazards were used as physicochemical indicators to quantitatively estimate a value for their environmental effects for inclusion in the costs benefits analysis.



impact

likelihood		High (4)	medium(3)	low (2)	Negligible (1)
	likely (4)	16	12	8	4
	possible(3)	12	9	6	3
	Unlikely(2)	8	6	4	2
	Rare(1)	4	3	2	1

value of 1-3	are typically perceived as low risks and unlikely to need specific application
Value of 4-6	Medium risk and manage by specific monitoring or response procedures
Value of 8-16	are perceived as high risks and should be unacceptable and it require executive management attention

Figure 4-6 Simple risk matrix for assessing the environmental risks

4.2.2.4 Develop Risk Management Strategies

Different wastewater management strategies were assessed to determine the best management strategies that could be applied to reduce the risks from selected principle hazards using a heuristic approach. These strategies include:

1. Treatment Options
2. On-farm measure such as irrigation systems
3. Crop selection

4.3 Costs-benefits Analysis

Costs-benefits (CBA) analysis is a well-known economic technique that can be used for assessing and comparing the performance of alternative wastewater reuse strategies, hence supporting the selection of the optimum strategy. In this study, CBA was used to decide which of effective risk management strategies were economically justified (in which the expected benefits are greater than the costs) and which would generate greater economic return compared to a baseline (without project) scenario.

Figure 4-7 provides the analytical framework For the CBA used in this study. The economic model captures and compares all the costs and benefits, using the following technical efficiency indicators: Net Present Value (NPV) and Benefit-Cost Ratio (BCR). The model was run for 30 years, with all costs and benefits after the initial year being discounted at a rate of 3% per year and the year of cost data used was 2010. Because of the situation in Libya has been volatile and instable during the time conducting this research, 2010 prices have been selected since they are a bit more comparable.

The discount rate was selected as the average of the annual rate of GDP growth for Libya for the period from 1990 to 2010. Data from the case study was used where possible and this data was supplemented with other best available sources of data from regional or international sources. More details on the cost-benefit analysis are presented in chapter 8.

4.3.1 Costs

Costs were estimated for alternative strategies over a 30-years lifecycle, the cost components assessed in this research are discussed in sections 4.3.1.1 to 4.3.1.4 below.

4.3.1.1 Capital, Operational and Maintenance Costs

Capital costs are one-time costs and include upgrading an existing WWTP or the installation of a new unit or the installation of new infrastructure for conveying and distributing the treated wastewater to the irrigation areas (pipes, tanks, reservoirs, pumps, etc.). Operational and maintenance costs typically include the energy required for treatment, conveyance and distribution, labour, chemicals and raw materials, monitoring and analyses, and equipment depreciation.

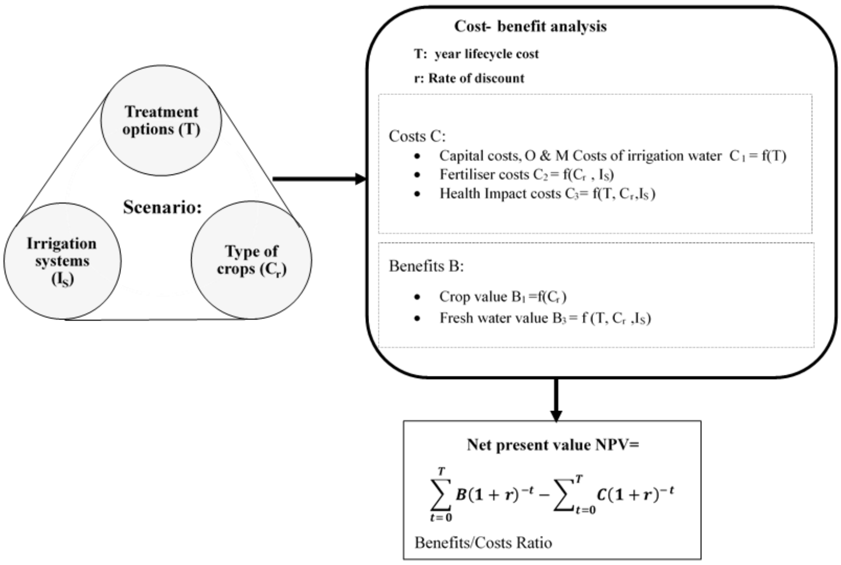


Figure 4-7 Analytical framework of Costs- benefits analysis

To determine these costs it was necessary to collate information and data about the existing wastewater management practices and treatment facilities including current and future volume of wastewater, wastewater collection systems, and conditions, routine maintenance costs of operating treatment facilities and treatment plant capacity and technology, in addition to the cost of possible interventions. Some of the cost data were collected from project reports in the case study area. However, due to the limitation of secondary data from the case study area, cost data for various options was assembled from regional or international data, or was assumed based on information in the literature.

4.3.1.2 Fertiliser costs

Reuse of wastewater in agriculture could result in reductions in chemical fertiliser demands and subsequent savings in fertiliser costs due to the exploitation of the nutrients present in the wastewater. However, this depends on many factors including but not limited to: the crop type and yield, crop water requirement and the nutrient concentrations in the wastewater. For the alternative scenarios being assessed the fertiliser costs at the farm gate were estimated based on the range of fertilisers available in the local market in the case study area.

4.3.1.3 The cost of health impacts

For the calculation of the economic value of health impacts, the total DALY loss from alternative scenarios was considered and associated with an economic loss (salary loss) using the following formula:

Economic value = Total DALY loss x Annual Wage Equation 4-3

4.3.1.4 Costs of public information

These costs include the cost of public education, awareness initiatives, demonstration programs and promotional health programmes and activities. These would be done in order to achieve public acceptance of recycling wastewater, persuading farmers to change their agricultural practices or encouraging people to consume wastewater irrigated products. These costs were not included in this research due to a lack of data and also time constraints.

4.3.2 Benefits

The yield of net benefits depends on many factors such as the cost of water abstraction for irrigation, irrigation practices, the cost of water abstraction and supply for other sectors, the cost of fertilizer, the value of crops, the current situation with regard to wastewater collection and sanitation systems, and current wastewater treatment and management. For the purposes of this study, the benefits were estimated in terms of crop value and fresh water value as outline in the following sections.

4.3.2.1 Crop values

Crops yield may increase due to the availability of a reliable source of water supply to farmers and the exploitation of organic fertilizer. However, wastewater reuse could restrict irrigation of certain crops due to the associated health and environmental impacts. In this study, the value of crops is mainly a function of their yield and marketability, and can be estimated using the following function:

Crop value = crop yield × crop price Equation 4-4

4.3.2.2 Fresh Water value

This includes water being saved or exchanged with other users. In this research, the fresh water value was considered as the avoided marginal O&M costs of transporting water via the man-made river for agricultural supply

4.3.3 Sensitivity Analysis

Sensitivity analysis was conducted to assess the robustness of the economic model results using different input values for the main variables. Sensitivity analysis was performed in a simplified approach for both the costs and benefits associated with alternative strategies in order to identify which economic variables are critical in determining the costs-benefits indicators. For the cost side, the analysis was conducted by varing one or two of cost- variables values with selected fraction (e.g ±0.1) below and above the applied value. For the benefits side, the analysis was undertaken by varying the value of the crop by selected fraction (e.g ±

0.1). The analysis was undertaken to ascertain the effects of variations in the discount rate on the costs- benefits indicators by increasing the discount rate from 3% to 8%, 10%, and 12%.

4.4 The development of the evaluation model

An Excel spreadsheet was used to develop a tool that can be used to assess alternative wastewater reuse strategies. The workbook that was developed consists of a number of sheets that incorporate a model for environmental risk assessment, the results of the MC-QMRA simulation programmes and a model for costs and benefits analysis. Users will get access to key performance figures, including crop yields, water and fertiliser demands, risk assessments and economic model results, in addition users will also be able to retrieve detailed model outputs. A guidance about how to use the tool is provided in Annex 4. The tool is available on the CD attached with the thesis.

4.5 Verifying and validating the approach

The research was based on data from a case study of Misurata in Libya. Given the extreme scarcity of water in this area, wastewater reuse has the potential to offer a viable alternative to the irrigation water currently used. At present it is impossible to determine the relative merits of different domestic wastewater reuse strategies in Misurata due to a lack of detailed data on current farming practices including crop types, current irrigation water sources, current fertilizer use, post-harvesting practices. This data will form the basis of the baseline scenario currently in operation in Misurata.

Once the baseline data is obtained, it will be possible to quantify the costs and benefits of the current scenario and develop a number of alternative wastewater reuse scenarios that are compatible with the current crops being grown and the farming practices that are currently used. The study will be of little benefit unless the proposed scenarios can be applied to the crops that are grown or fit within the farming practices that the farmers routinely use. If this is not the case, then farmers will be reluctant to take up any alternative wastewater reuse strategy.

In order to obtain good quality data, the initial plan was to undertake fieldwork in Misrata in order to collect data and information from a range of different sources with a different approach depending on the information needed and the target group. However, due to the continued uncertainty regarding the situation in Libya and health and safety concerns raised by the University, the field work was vetoed, and an alternative approach was required to gather the required data and information needed for completing this study. The following sections provide the initial approach and the applied approach for data collection.

4.5.1 Initial Data Collection Approach

Originally, the research was based on both primary and secondary data from a case study that was to be carried out in Misurata in Libya. The primary data was to be obtained through interviews with key stakeholders, including farmers, within the study area, and some wastewater quality tests were to be undertaken. In addition to the primary data obtained from the farmers, secondary data was to be collected from government officials, wastewater treatment plant operators and disposal agency workers and alternative sources in the literature. Annex 5 provides more detail on the original plan for data collection.

4.5.1.1 Primary Data

Primary data was to be obtained using a number of different approaches:

- **Observation**- Site visits were organized to visit different locations including farms, crop markets, treatment facilities and disposal sites to obtain information.
- **Structured interviews** with farmers in Misrata – this approach was chosen because it is a useful standardized tool to collect factual information and provides a reliable source of quantitative data about current farming practices in the case study area. The plan was to ask Farmers through structured interview to provide information about their agricultural practices which includes information related to:
    - Crops (type- yields- seasons)
    - Irrigation systems (type-cost-time- frequency)
    - Agriculture practice (labour or mechanization)
    - Harvesting and marketing practices
    - Fertilizer applications (type-cost)
    - Water supply (source, quality, and cost)
- **Open questionnaires** with key informants including government officials, treatment plant operators, and waste disposal agency workers – this approach was chosen because it allows different type of data and information to be obtained from each of the selected key informants. It would be very difficult and time consuming to conduct a structured interview that can be used to interview each of the key informants. Also using open questionnaires give better flexibility for new questions which may arise during the interview to be asked impromptu. A number of key informants to be interviewed to provide information related to water resources management, water supply, agricultural activities, and wastewater collecting, disposal and treatment facilities in the city. Before undertaking the fieldwork, a number of organisations and authorities have been identified based on the required data. These organisations were identified based on the researcher's

in-depth knowledge of the region and the organisational structure that currently exists. These organisations are listed below.

- Housing and infrastructure board (housing and infrastructure ministry)
- Engineering consulting office for utilities
- General Water and Sewage Company
- Misurata sewage treatment plant
- Wastewater Treatment Plant in Libyan Iron and Steel Complex
- General water authority (middle region)
- The authority for the utilization of Jabel Hasawna- Jefara Water system of the man-made river.
- Ministry of agriculture and livestock in Misurata
- Agriculture development committee

In addition to:

- treatment plant operators in their working place
- disposal agencies workers in their working place

- **Field tests** – The purpose of this is to obtain data on the chemical and microbial quality of wastewater from a variety of sources including wastewater treatment facilities and soak-away tanks. This information is important in order to assess the ‘value’ of the wastewater in terms of nutrients and ‘risks’ associated with the presence of pathogens, salinity, and heavy metals. Chemical and physical constituents of wastewater from wastewater treatment and collecting tanks includes EC or TDS, total N, NO_3, NH_4, P, K. This was to be done by taking samples of wastewater from treatment facilities and collection tanks and taking them to the local laboratory (University or other government labs). With regards to the microbial testing a field kit was planned to be used to measure total Faecal Coliforms or E-coli in the wastewater from wastewater networks, treatment facilities and collecting tanks.

4.5.1.2 Desk study and Secondary Data

Where it is not possible to collect primary data then secondary data sources are to be used including both published and unpublished sources of data and information. Secondary data will be obtained through:

- Interviews with key informants to determine the availability of secondary data and the possibility of access to that data. The types of secondary data that may be available would be:
    - Wastewater treatment facility data including types of treatment used, costs, etc.
    - Wastewater quality data from laboratory reports
    - Official documents and reports from related government departments and authorities including information on wastewater collection, sources of water supply, regional agricultural data.
- Literature Review includes international and national journal articles and reports, fact sheets, edited and textbooks, and websites.

4.5.2 Data collection approach applied in the study

Plans for completing the fieldwork necessary for the research was vetoed for Misurata in Libya and also for a second time for an alternative case study to be carried out in Sfax inTunisia. This was due to the FCO advice which was against all travel to both Libya and Tunisia as a consequence of instability and unrest in the region at the time of this study. As a result of many constraints including time, financial issues, visa requirement and the language barrier, it was extremely difficult to select another case study area that was appropriate for this research. Therefore, as it was not possible to collect primary data, secondary data sources were used to collect the required data and information which includes both published and unpublished sources from the case study (Misurata-Libya), and regional and international sources. The most relevant and potentially useful sources of data and another information gathering can be summarized as following:

a) Contact with key informants (via emails or phones) to determine the availability of secondary data and the possibility of access to that data from the case study area. The types of secondary data that may be available would be:
    - Wastewater treatment facility data including types of treatment used, costs, etc.
    - Wastewater quality data from laboratory reports
    - Official documents and reports from related government departments and authorities.

b) The Literature review which included: Journal articles, edited and textbooks, international reports, fact sheets and websites to collect data related to Libya, regional data or international data. Both online search and hand search methods were implemented to gather the information. Table 4-3 illustrates the alternative approach to collecting the required data and the annotations 1, 2, and 3 represents the first, second and third alternatives respectively for collecting these data.

4.5.3 Implication of the change in data collection method:

It must be highlighted at this point that, although the most appropriate secondary and proxy data have been carefully selected from regional and international sources, using secondary and proxy data might have implications for the accuracy of the data and subsequently on the accuracy of outcome results Below for some critical parameters is a reflection on the probable impacts of the assumption made on the results:

- Wastewater quality: some of wastewater quality parameters, particularly pathogen content (e coli and ascaris eggs) were selected using typical data from the literature for warm climates in developing countries. For the key pathogen indicators, their concentrations in wastewater were determined by using published ratios between key pathogens and E. coli that has been used in many studies in developing counties. Much of this literature relates to West Africa which can be used as representative to this case study to represent the worst case scenario (as the prevalence of the diseases caused by these pathogens is much lower in Libya than in these counties).
- Leaching requirement and salt tolerance of crops: The salt tolerance data that were used to calculate the leaching fraction was selected from the literature and based on the assumption that the soil is well drained, that leaching of 15% to 20 % is achieved and that the soil is well drained. This last assumption is valid since the soils in the case study area are mostly sand soil to sandy loam and very low in nitrogen and organic matter. This information is based on the researcher’s own knowledge and confirmed by the literature (Al-Idrissi, Sbeita et al. 1996, Gerged 2009).
- Cost data for construction new sewerage system: These costs were estimated based on the cost of installation of new sewerage in one district of the city assuming the city is homogenous, and the cost increases proportionally with the population. Data for the original cost estimate was reported in (Housing & Infrastructure Board, 2013). These costs are estimates only and there is uncertainty around them as the cost of sewerage is driven by site-specific conditions. This would be an area where improved accuracy of assumptions would be a valuable contribution to improving the validity of the overall analysis.
- Costs of O&M of irrigation systems: due to lack of data with regards to the additional costs that may be required for the O& M of irrigation systems as results of using wastewater these costs were not included. However, as an economic costs at national level these costs may not be significant compare to other capital and O&M costs.

Table 4-3 Alternative methods for collecting required Data

	Framework component	**Required Data**	**Literature**		**Secondary data**
			Related to Libya	**international**	**key informants**
Agriculture Data	Health risk assessment (QMRA) AND Environmental risk assessment	Types of crops.	2		1
		irrigation practice and technique	2		1
		Agriculture practice (Labor or mechanization based)		2	1
Wastewater data	Capital and operation cost	Current and future volume of wastewater	2		1
	Health risk assessment (QMRA) AND Environmental risk assessment	Quality of raw wastewater: - Chemical tests - microbial tests	1	2 2	
		Quality wastewater outflow from treatment plant - Chemical tests - Biological tests	1	2 1	
		Quality wastewater outflow from soak-away tanks	1	2	
Sewage network and treatment plants	Capital and operational cost	Treatment plants capacity	2		1
		Treatment technology	2	3	1
		Sewage collection systems	2		1

	Framework component	Required Data	Literature		Secondary data
			Related to Libya	international	key informants
Health data	Health risk assessment QMRA	Endemic Waterborne disease		1	
		Rate of mortality and morbidity due to above disease		1	
		Incidence of diseases		1	
		Diseases –infection ratio		1	
		Exposure (A possible route of transmission of causal pathogens)		2	1
Economic data	Value of fresh water	Cost of water abstraction for irrigation: • Cost of water from manmade river • Cost of privet well (drilling and pumping) • Seawater desalination	2	3	1
	Capital and Operational cost	Capital cost of wastewater treatment options	2	3	1
	Capital and Operational cost	the cost of collection wastewater and distribution	2	3	1
	Capital and Operational cost	Cost of operation and maintenance	2	3	1
	Agriculture value	Cost of fertilizer	2		1
	Agriculture value	Value of crops	2		1

1. The first option,
2. Second option
3. Third option

4.6 Case Study of Misurata

Misurata is the third largest city in Libya with a population of around 500,000 in 2012. It is in the northwest of the country about 200 km east of the capital city Tripoli (Figure 4-8). The city has been recognised for its commercial and industrial activities. In addition to these activities, peri-urban agriculture has had a niche function for urban food supply (particularly perishable vegetables and fodder produce) to the city. Misurata as any other city in the country experiences serious water scarcity. The absence of surface water resources along with the low rate of precipitation (250 mm /year), make the city heavily reliant on groundwater for its water supply. Around 95% of municipal, commercial and industrial demands are supplied from the man-made river, whereas agricultural activities rely predominantly on local groundwater for its supply(General Water and Sewage Company, 2012).

While the city is facing severe water stress, there is no consideration given to the reuse of wastewater as a non-conventional resource that would help to close the gap between water supply and demand, particularly in agriculture. Instead, only a small proportion (<5%) of the domestic wastewater generated in the city is reused for irrigating fodder crops, and the rest is either discharged to the sea or into lagoons south of the city or collected in soak-away tanks and eventually disposed of to the marsh(General Water and Sewage Company, 2012).

Figure 4-8 Case study of Misurata Libya

4.6.1 Target farms

Overexploitation of local groundwater resources by agricultural activities has resulted in significant water quality deterioration and saline intrusion problems (General water authority, 2005). In responding to overcome water shortage problems particularly for agriculture, the government has undertaken new projects to increase the water supply from the man-made river to satisfy agriculture demands in the city. However, due to the instability and unrest in Libya, the project had been suspended during the time of conducting this research (the man- made river authority, 2010).

Since this research will focus on providing data on viable alternatives to current water supplies for agriculture, information from the new project was used to inform this research. For example the new project documentation includes a list of farms that will be included in this new supply network and this was used in this study to develop the baseline scenario. Therefore, these farms were the ones that were included in this study. As a result, 248 farmers from agricultural project farms which are located west of the city in Al Dafinyah were selected as target farms with area of 30 hectar per farm (Figure 4-9). Currently, some of these farms rely on private boreholes which are likely to be drilled illegally and do not follow the national standard of drilling, contributing to aggravated groundwater deterioration problems. The other farms rely on rainfed cultivation of mainly olive trees and grains(Ministry of agriculture and livestock, 2012).

Figure 4-9 Location of target farms

4.6.2 Irrigation Water Supply

4.6.2.1 Local Ground Water

Previously, state wells which are located in Al Dafiniyh were used to supply the agricultural project farms (case study farms) which were managed by the Ministry of Agriculture in cooperation with the General Water Authority. However, currently, all of the wells are out of order due to water quality deterioration. This is has led to a decrease in the productivity of these farms and as a result they became in poor condition. To overcome this problem, many farmers have drilled their own wells mostly illegally and these do not follow the national standard of drilling which has led to groundwater salinity from the top layers where sea water intrusion is a significant problem(Ministry of agriculture and livestock, 2012, General water authority, 2005).

Currently, most of the operated wells pump the water from the aquifer with varying degrees of discharge and depth. Water quality ranges from moderately saline to saline. Table 4-4 shows the main ground water characteristic from wells of case study farms.

Table 4-4 The characteristic of water from currently operated wells(General water authority, 2005)

Groundwater borehole characteristic	
Depth m	200-500
Discharge m3 /hr	20-50
EC dS/m	3.9-9.2
TDS mg/l	2500-6000

4.6.2.2 Man-Made River

The Authority of Investment of the Hasouna- Gfara water system (phase 2) of Man-made river planned several projects for the distribution of water to different areas of demand in the coastal area in North –East. This was done to achieve the aim of conveying 2.5 million m^3 of water daily of which 70% was allocated for agricultural demand. One of these projects is to supply Agricultural project farms (case study farms) and other farms in Al Dafiniyah at a rate of around 30000m^3/day. The project consists of the construction of a transport pipeline, concert tank for pressure breaking and internal distribution network to supply all the farms. However, as mentioned earlier this project was suspended due to the unrest in Libya during the time of conducting this study and the current completion rate is only around 10% (the man- made river authority, 2010)

4.6.3 Wastewater infrastructure and management

In general, the amount of wastewater generated in the city is estimated to be 80% of total water consumption. Only about 30% of this amount is collected by sewage networks and the other 70% is collected using soak-away tanks. In 2012 the total domestic sewage flow was estimated to be around 116000 m^3 /day based on an average daily water demand per capital of 300 litres. Table 4-5 Total water demand and wastewater generated in the city for the years of 2012 and Figure 4-10 shows what happens to the wastewater in terms of treatment and disposal (General Water and Wastewater Company 2012, Housing and infrastructure board, 2010, Engineering consulting office for utilities, 2005a).

4.6.3.1 Current wastewater treatment plant

The main wastewater treatment plant in the city was installed in 1989 and is located in the south of the city in the Al Sickat area which is 13 km from the city centre and 70 m above the sea level. It is designed to treat an average capacity of 24000 m^3/day, and maximum influent of 72000 m^3/day in emergency cases. The plant has only preliminary treatment and biological treatment followed by disinfection units. The biological treatment is activated sludge using aeration basins followed by settlement tanks, sludge thickening and sludge drying beds(General Water and Wastewater Company 2012) (Figure 4-11).

Table 4-5 Total water demand and wastewater generated in the city for the years of 2012(General Water and Wastewater Company 2012)

City Population	Average Water consumption/capital m^3/day	Domestic Sewage Flow m^3/day
500,000	0.3	0.24
Total	150,000	120,000

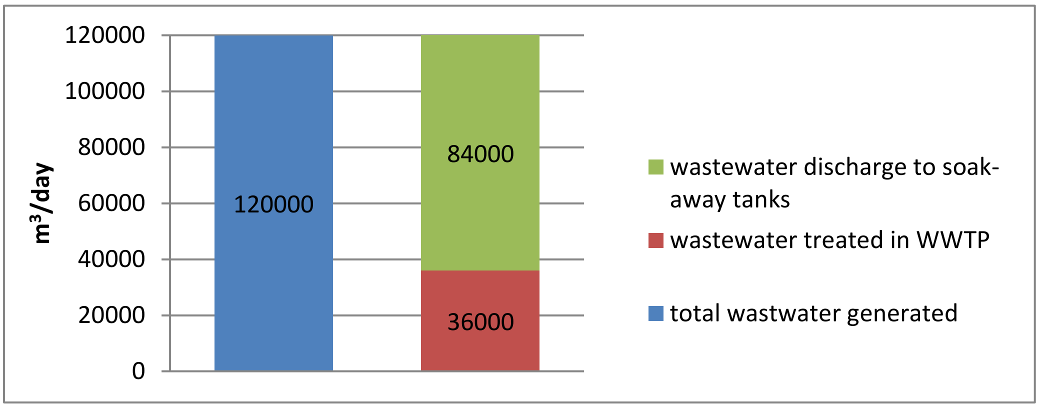


Figure 4-10 Estimation of wastewater generated in Misurata 2012

Currently, the plant receives an inflow about 30000 m^3/day which over the design capacity this inflow is mainly domestic wastewater with a minor contribution of industrial wastewater and represents only 25% of wastewater generated in the city, which comes from the parts of the city that connected to sewerage systems. The inflow is mainly domestic wastewater with a small proportion of commercial wastewater that is illegally connected to the sewerage network(General Water and Wastewater Company 2012)

Generally, the plant works with sufficient efficiency, however, it has many problems including, damage to the chlorination unit resulting in the shutting down of the unit, and deterioration of some elector-mechanical equipment (General Manager, wastewater treatment plan 2013, General Water and Wastewater Company 2012, engineering consulting office for utilities, 2005).

Treated wastewater is used in the Forage Crops Production Project. The project uses only 4000 m^3 and the excess treated wastewater is discharged to emergency lagoon. These lagoons are located near the treatment plant with a total area 8 hectares. They consist of a receiving reservoir with a capacity of 24000 m^3 and two storage reservoirs with capacities of 119000 m^3 and 161000 m^3 and two sludge drying beds (General manager, wastewater treatment plan 2013, General Water and Wastewater Company 2012, Engineering consulting office for utilities, 2005) (Figure 4-12).

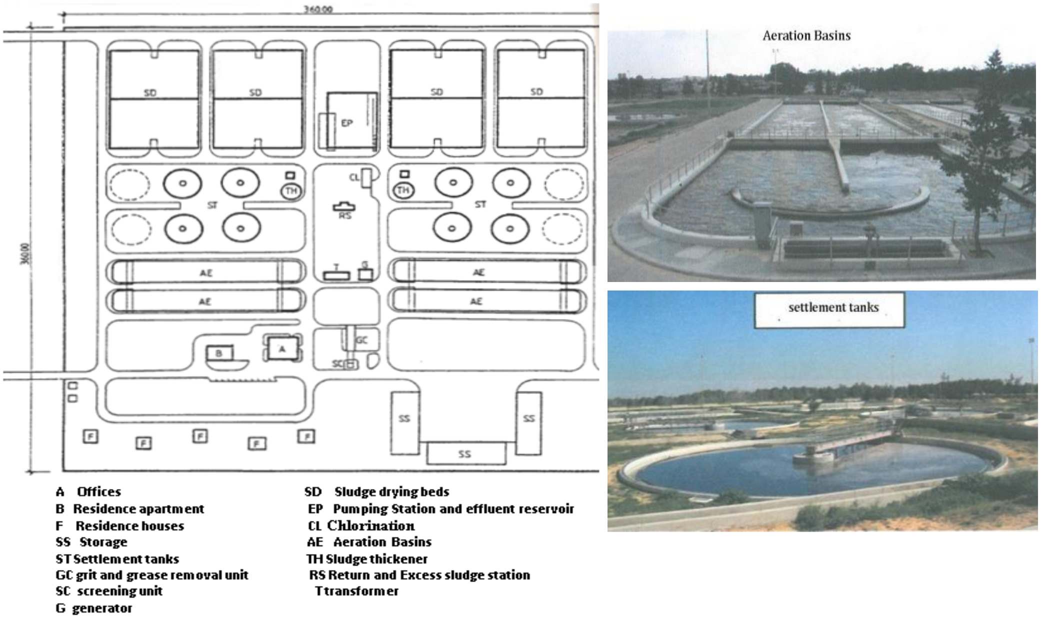


Figure 4-11 Layout of Misurata wastewater treatment

Figure 4-12 Emergence lagoon

4.6.3.2 Soak -away tanks

As mentioned previously around 70% of the city uses soak-away tanks for wastewater collection. These tanks are usually owned by the citizens and are made of permeable walls and an open base to allow wastewater to infiltrate. The size of these tanks is dependent on the size of the served building. In general, these tanks take from 10 to 15 years to be completely full after that they will need to be emptied one or twice per month depending on the size. It was estimated that when these tanks are emptied only 10% of the septage can be sucked from these tanks and discharged to the marsh(General Water and Wastewater Company 2012).

4.6.3.3 Wastewater Characteristics

With regards to the wastewater characteristics, some of chemical qualities were obtained from secondary data from the case study (Engineering consulting office for utilities, 2005b, wastewater treatment plan, 2013), while information on the microbiological qualities and other chemical characteristics were estimated based on typical values of physical-chemical characteristic of wastewater in developing countries from the literature (Wu et al., 2009, Carey and Migliaccio, 2009, Henze and Comeau, 2008, Al-Sa'ed and Hithnawi, 2006, Sperling and de Lemos Chernicharo, 2005, Tchobanoglous et al., 1991, WHO, 2006, Bahri, 1998, Feigin et al., 2012). Table 4-6 presents the chemical and microbiological qualities of the wastewater generated in the case study, whereas Table 4-7 provides the physical-chemical and microbiological characteristic of wastewater in developing countries taken from information from the literature and Table 4-8 septage characteristic from cesspool and Typical wastewater characteristic from individual residence in published literature.

Table 4-6 Chemical and microbiological qualities from WWTP of Misurata

	Units	Raw wastewater (influent)[a]	Effluent from exciting WWT	Collecting tank
BOD5	mg/l	200	10	465
TSS	mg/l	150	15	3647
TDS	mg/l	3050	3000	2440
EC	dS/m	4	4	3.8
TN	mg/l	-	-	-
Ammonia	mg/l	45	30	82
NO2	mg/l	-	-	-
No3	mg/l	-	-	-
PO4-P	mg/l	-	-	-
TP	mg/l	-	-	-
K	mg/l	-	50	-
Total coliforms	TC/100ml	-	-	-
FC or E coli	FC/100ml	-	-	-
Helminth Eggs	Eggs/ml	-	-	-

a. based on test reports from wastewater treatment plant 2013

b. based on the result of wastewater test from vacuum truck (2005)

Table 4-7 Physical-chemical characteristic of raw and secondary treated wastewater in developing countries

Parameter	Unit	Wastewater physical-chemical characteristic Tunisia [a]		Typical values of raw WW [b]
		influent	Effluent	
BOD5	mg/l	248.6	35.5	250-400
TSS	mg/l	359	42.4	200-400
TDS	mg/l	2950	2610	500-900
NK	mg/l	67.7	30	30-60
TN-N	mg/l	-	-	20-85
NH4-N	mg/l	67.4	26.2	20-45
NO3-N	mg/l	0.84	9.5	0-2
NO2-N	mg/l	2.62	2.48	0
TP-P	mg/l	9.43	3.5	4-15
PO4-P	mg/l	6.17	2.34	4-10
Organic P-P	mg/l	-	-	1-5
Total coliforms	TC/100ml	-	-	10^{7} - 10^{10}
FC or E coli	FC/100ml			10^{6} - 10^{9}
Helminth Eggs	Eggs/ml			10-1000

a. Descriptive statistics of average element concentration for influent from 15 wastewater treatment plants in Tunisia (Bahri, 1998).

b. Typical values of physical-chemical characteristic of raw municipal wastewater with minor contributions of industrial wastewater (Wu et al., 2009, Carey and Migliaccio, 2009, Henze and Comeau, 2008, Al-Sa'ed and Hithnawi, 2006, Sperling and de Lemos Chernicharo, 2005, Tchobanoglous et al., 1991, WHO, 2006, Bahri, 1998, Feigin et al., 2012)

Table 4-8 Septage characteristic from cesspool and Typical wastewater characteristic from individual residence in published literature

Parameter	Palestine (average)[a]	Typical values of raw WW[b]
BOD5	434	216-540
TSS	3068	240-600
TKN	150	31-80
Ammonia -N	91	7-40
TP	-	10-27
PO4-P	13	6-17
Total coliforms	-	10^{7} - 10^{10} /100ml
FC	-	-
Helminth Eggs	-	-

a) Source: (Al-Sa'ed and Hithnawi, 2006),

b) typical characteristics of Wastewater from individual residence based on flow of (380l/capita/d and 150l/capital/d) (Tchobanoglous et al., 1991)

4.6.4 Developing Potential Wastewater Reuse Strategies in Agriculture

Risk management is an essential component for developing any wastewater reuse strategies. Protecting public health and reducing or eliminating environmental impacts could be achieved through many options, these options can be categorised into two main approaches: (i) wastewater treatment to reduce or eliminate concentrations of pathogens in wastewater and to control chemical constitutes; and (ii) post-treatment management measures to limit public exposure to wastewater and mitigate the environmental impacts from wastewater irrigation. These measures include but are not limited to: crops restriction, improved application measures, post harvesting measures. Development of potential management strategies for any given setting depends on economic, institutional and technological and biophysical factors and also a socio-cultural aspect.

In this research, an appropriate representative range of wastewater management strategies have been identified based on technological feasibility and available information about agricultural practices in the case study area. Figure 4-13 and Table 4-9 presents the selected management strategies for developing the evaluation approach.

4.6.4.1 Treatment options

A wide variety of wastewater treatment options are available to generate a range of effluent qualities, including primary treatment (such as primary sedimentation and lagoon treatment), biological treatment (such as activated sludge, trickling filters, oxidation ditches) natural treatment processes (such as waste stabilisation ponds and wetlands) and tertiary treatment and advanced treatment (such as membrane techniques, chemical treatments and carbon adsorption) (George et al., 2003). Different combinations of these options can be set up and some of these combinations may also include other simpler processes such as septic tanks, and sand filtration. The wastewater treatment options considered in this research were selected to represent primary, secondary and advanced treatment. The selection was based on (i) suitability for the case study climate and condition, and (ii) the potential for adaptation. These options are divided into on-farm treatment (three tank systems and sand filters) and wastewater treatment process (conventional activated sludge with disinfection, waste stabilised ponds, conventional activated sludge with biological nitrogen removal and disinfection, and advanced treatment) as illustrated in Table 4-9. These particular options were selected because they have been used in other cities in Libya.

4.6.4.2 On farms measures

There are many on-farm management measures that can be applied after wastewater treatment to reduce the risks from irrigation with wastewater. However, because it was not possible to carry out the case study to gather information related to farming and post harvesting practices in the case study area the only on-farm post treatment practice that has been included in this study is the type of irrigation system used. The reason that this was included is that it is currently a commonly used system in the study area (based on Research knowledge, confirmet senior employee in Agriculture development committee. Ministry of agriculture and livestock in Misurata).

4.6.4.3 Crop selection

Based on the commonly cultivated crops in the case study area (Ministry of agriculture and livestock, 2012), a number of field crops, fodder grasses, and fruit tree types were identified as potential alternative crops patterns that would be suitable for irrigation with wastewater and these are shown in Figure 4-13

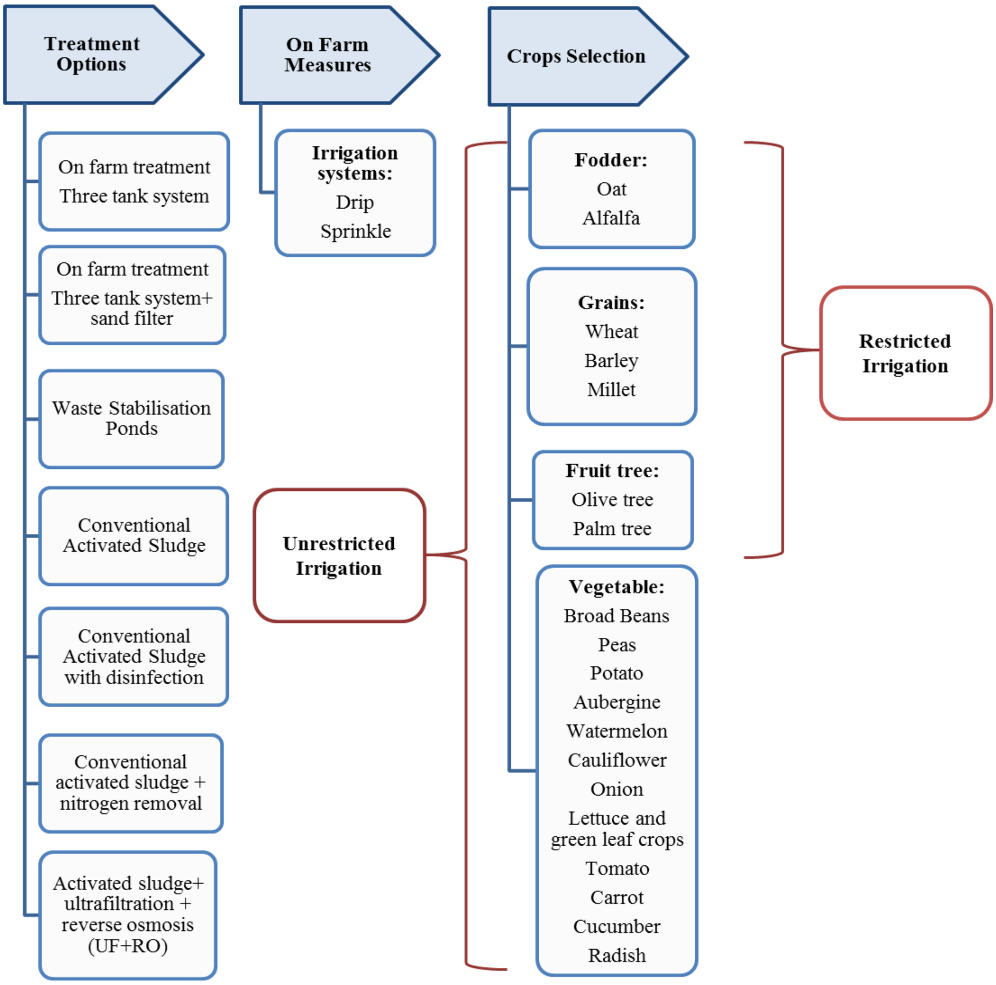


Figure 4-13 Potential wastewater reuse strategies considered in the research

Table 4-9 Wastewater management options

Wastewater collecting option	Wastewater treatment options	Remarket
septic tank	on-farm treatment three tanks system	Requires upgrade soak away to the septic tank, the provision of on-farm facilities and well-regulated and properly financed collection services.
septic tank	On-farm treatment three tanks system+ sand filter	Requires upgrade soak away to the septic tank, the provision of on-farm facilities and well-regulated and properly financed collection services.
septic tank	WSP	Requires upgrade soak away to septic tank, incentives for effluent to be delivered to WSP
Sewerage network		Centralized or decentralized, Require construction and operation of sewerage (mostly with pumping)
Sewerage network	WWTP (conventional activated sludge)	Require construction and operation of sewerage (mostly with pumping), and effluent storage
Sewerage network	WWTP (Activated sludge+ Biological Nitrogen Removal)	
Sewerage network	WWTP (Activated sludge+ Ultrafiltration+ reverse osmosis)	

- WWTP: wastewater treatment plan, WSP: waste stablisation ponds

Chapter 5. Health risk assessment

5.1 Introduction

There is well established literature examining the general health risks associated with the use of wastewater in agriculture using Quantitative Microbial Risk Assessment (QMRA)(Seidu et al., 2008, Mara and Sleigh, 2010b, Mara and Sleigh, 2010c, Mara and Sleigh, 2010a, Seidu and Drechsel, 2010, Evans and Iyer, 2012). In this chapter Quantitative Microbial Risk Assessment QMRA was used for assessing the health risks associated with wastewater reuse in agriculture; this methodology never been applied to assess health risks from wastewater irrigation in Libya. Thus, this chapter represents the first attempt to systematically apply (QMRA) to assess different strategies for wastewater reuse in agriculture.

This work is an application of accepted method therefore, it is not on its own is novel. However, in the following chapters it will be demonstrated how this can be combined with other approaches which makes it novel.

For estimating the health impacts from different wastewater reuse strategies for agricultural purposes using QMRA, the following steps were undertaken:

1. Hazard identification,
2. Dose–response analysis,
3. Exposure assessment, and finally
4. QMRA-MC simulation.

5.2 The Key Pathogens used for the health risk assessment

For the health risk assessment, four reference pathogens were used. Norovirus, Salmonella, Ascaris and Giardia were chosen as representative organisms for viruses, bacteria, helminths and protozoa respectively. These index pathogens have been selected based on information provided by the World Health Organisation (WHO, 2009, 2015, 2011) and a review of epidemiological studies from Libya, the Middle East and North Africa (the review is provided in Annex 3).

Based on the litreture review (Annex 3), Noroviruses and HAV and HEV are the most singnificant viral pathogens that seem to have a potential risk on Libyan population from wastewater reuse. However, for the purposes of this study Noroviruses are selected as viruses indecator. Noroviruses are considered to be the most common cause of non-bacterial gastroenteritis affecting both children and adults worldwide (Ushijima et al., 2014, Widdowson et al., 2005, Patel et al., 2008, Matthews et al., 2012). Two studies were carried out in Tripoli in 2008 and they reported that norovirus is also a predominant agent found in diarrheic Libyan children with a rate of 15.5% and 17.5% (Rahouma et al., 2011, Abugalia et al., 2011).

For bacteria indicator, Non-typhoid Salmonella is considered in the literature as the second major cause of acute diarrhoea among Libyan children with an average prevalence rate that varies from 6% to 19%, (Ghenghesh et al., 2001, Ghenghesh KS et al., 2008, Rahouma et al., 2011, Ali et al., 2005). Enteric fever caused by Salmonella Paratyphi and Salmonella Typhi is considered an endemic disease in Mediterranean North African countries with a median incidence of 10 to 100 cases per 100,000 persons. According to recent estimates of the Global and Regional Disease Burden in 2010 supported by the WHO the burden of typhoid and paratyphoid fever in this region is 25 cases per 100,000 (Kirk et al., 2015).

A study on parasitological contamination in salad vegetables in Tripoli in Libya indicated that Ascaris eggs have the highest contamination rate in salad vegetables in Tripoli (it was detected in 68% of the selected samples) (Abougrain et al., 2010). Additionally, a few studies looking at intestinal parasites in school pupils aged 5 to 17 years in different Libyan cities indicated that the overall prevalence of infection of Ascaris lumbricoides among children ranges from absent to 35.5% (Ben Musa, 2007, Kasssem et al., 2007, Ben et al., 2007, Al Kilani et al., 2008, Sadaga and Kassem, 2007, Jacobsen et al., 2007). Some of these studies have also indicated that Giardia is one of the most common intestinal parasites among children with a prevalence rate ranging from 1-30% (Bernawi et al., 2013, Kasssem et al., 2007, Ben et al., 2007, Al Kilani et al., 2008)

In general, none of the key organisms are directly investigated and detected in wastewater treatment facilities in most developing countries including Libya. Therefore, their potential concentrations in wastewater were determined by extrapolation using published ratios between key pathogens and *E. coli;* these have been used in many studies in developing counties particularly in Africa and are therefore considered to be appropriate when used in this case study (as the prevalence of the diseases caused by these pathogens is much lower in Libya than in these counties). Ratios ranging from $1:10^5$ to $1:10^6$ were used to predict the concentration of norovirus and salmonella in wastewater (Mara and Sleigh, 2010c, Howard et al., 2007, Labite et al., 2010, Seidu and Drechsel, 2010, Gerba et al., 2008); and ratios ranging from $1:10^6$ to $1:10^7$ were used for Giardia (Howard et al., 2007).

A review of the literature found limited information relating to the quality of wastewater from Libya. Therefore, the quality of raw wastewater and the incidence of the key pathogens were estimated based on typical values reported in the literature (Sperling and de Lemos Chernicharo, 2005, WHO, 2006). However, the original proposal was to actually measure the concentration of indicator bacteria (e.g. E coli) in wastewater from a number of different locations Misurata (raw wastewater, treatment facilities and soak away tanks) using field kits. The concentration of Ascaris eggs in raw wastewater in endemic areas was taken from (Mara and Sleigh, 2010a). Table 5-1 provides an overview of typical concentrations of *E. coil* and Ascaris eggs in raw wastewater.

Table 5-1 Typical concentration of E. coil and Ascaris eggs in raw wastewater (Sperling and de Lemos Chernicharo, 2005, WHO, 2006)

Indicator organism	Unit	values
E coli	Per 100 ml	10^8
Ascaris Eggs	Eggs/litter	100

5.3 Exposure scenarios

5.3.1 Restricted irrigation (Farmers' exposure scenarios)

Restricted irrigation in this study only involves irrigation of fodder crops, grains, and trees. The infection risks from restricted irrigation are associated with the ingestion of wastewater-saturated soil particles by farmers and field workers. The agricultural practices in the case study area are a mixture of mechanized agriculture (using a plough and sowing using tractors and associated equipment), and labour- intensive agriculture (as some activities such as harvesting vegetable crops are most likely to be done manually). In addition to this, the farmers and workers are more likely not to wear gloves, footwear (gumboots) and other protective clothing when working in wastewater-irrigated fields (this is based on the author's personal knowledge of the case study area, a structured interview with farmers for detailed information was prepared in the original proposal to confirm this information).

Therefore, for restricted irrigation the assumption is exposure is through labour-intensive agriculture which is the same assumption as that used by WHO (2006) but without pathogen die-off. The risk was estimated from ingestion of 10–100 mg of soil per person per day for 150 days per year. It has been reported that the quantity of soil that could be transmitted to the mouth via farmers' or field worker fingers and then be ingested is up to ~100 mg per person per day of exposure (Haas et al., 1999, WHO, 2001). The 150 working day per years is to represent a person working for three days per week on his or her own land. These exposures represent 'worst case' scenarios as agricultural practice in the case study is mixed between mechanized agriculture and labour- intensive agriculture.

For restricted irrigation, the consumer is assumed to be not at risk from wastewater irrigation due to crops restriction and only the farmer and their families are most likely to be at risk from wastewater irrigation. As the fieldwork could not be carried in the case study area, it was difficult to estimate the extent of the population that would be exposed. However, assumptions were made based on the researcher personal knowledge of the case study area together with some information from official reports and information gained from contacting key informants by email[2]. These assumptions are:

- **Farmers are live with their families on the farm and the the average family size is 6 (WHO 2010)**
- **The total number of farms is 248, with an average of five workers per farm**
- **Total population = 2,728 persons**

5.3.2 Unrestricted irrigation (Consumers' exposure scenario)

Unrestricted irrigation includes irrigation of all types of crops including salad crops and vegetables that may be eaten uncooked. The infection risks from unrestricted irrigation are associated with the consumption of wastewater irrigated crops that are eaten uncooked. Tomatoes and cucumbers can be considered as the most important fresh vegetables in the Libyan diet. Both are the main ingredients of the traditional salad known locally as "Slatha" which can be eaten with bread as a main meal especially during the summer or is often prepared as a light lunch or as dinner (Abougrain et al., 2010). For the purpose of this study, the tomato will be used as the key crop to examine the health impacts from the consumption of raw wastewater irrigated vegetables collected from the farm. Since detailed data regarding the typical amounts of tomatoes that are consumed per capita for the case study area is not available in the literature, the assumption is made based on data from a study in the neighbouring country of Egypt. In this study, it is assumed that 375 g of raw tomatoes are consumed per person per 2 days. Exposure is assumed to be via consumption of wastewater remaining on the surface of the tomato which is estimated to be between 3.5–4 ml after irrigation. Ingestion of contaminated soil attached to the crop is considered to be marginal (Evans and Iyer, 2012). In addition to these it is also assumed for the purposes of the worst case senario, there is no pathogen die off.

Most of the vegetables that are eaten raw and are sold in the city market (particularly leafy vegetables and root vegetables) are grown in the city's farms(Ministry of agriculture and livestock, 2012). It is known that the case study farms produce only a portion of these vegetables but unfortunately, an estimate of this portion is not available. Thus, an assumption had to be made and this was that only 30% of the vegetables are produced in the case study

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[2] Consulting farmers from case study & Mustafa Ayad : senior employee in Agriculture development committee. Ministry of agriculture and livestock in Misurata

farms. From the researcher's personal knowledge of the case study area, this assumption may be an overestimate, however this is deemed appropriate given that it is representing the worst-case scenario.

The total city population is around 500,000 persons, however due to the lack of information and data, it is difficult to estimate the total exposed population. Since 30% of the vegetables in the market are assumed to be a wastewater irrigated, the assumption was made that 30% of the population would be at risk from consuming raw vegetables irrigated with wastewater. Typically, children under two years are not expected to be at risk from consuming wastewater irrigated crops, however this assumption does not exclude children under two years old due to the lack of the data regards to the age distribution of the population. However, since the total number of children under two years old in comparison with total population is expected to be very small, excluding children under two years would most likely not make a significant change in the outcome of health impacts due to wastewater irrigation. Therefore, the assumption is:

Total population= 500,000 x 0.3 =150,000 persons

5.4 Dose-response models

The MC-QMRA simulation programme applies the beta-Poisson dose-response model for Salmonella (Haas et al., 1999, Seidu and Drechsel, 2010, Labite et al., 2010) and Ascaris (Navarro et al., 2009, Mara and Sleigh, 2010a) as it best describes the dose-response relationships. For Norovirus the dose-response dataset of Teunis et al. (2008) was used in place of the β-Poisson equation (Mara and Sleigh, 2010c). Based on experimental data developed by Rendtorff (1954) the exponential dose-response model was used for Giardia lamblia (Rose et al., 1991). Table 5-2 provides and overview of the dose–response parameters used in the MC-QMRA

$$\mathbf{P_I(d) = 1 - e^{(-rd)}} \quad \text{(Exponential dose-response model)} \quad \text{Equation 5-1}$$

$$\mathbf{P_I(d) = 1 - [1 + \left({d}/{N_{50}}\right)\left(2^{1/\alpha} - 1\right)]^{-\alpha}} \quad \text{(Beta-Poisson dose–response model)} \quad \text{Equation 5-2}$$

Table 5-2 Dose–response parameters used in the MC-QMRA

Organisms	Parameters	Type of model	references
Salmonella	N_{50} =23,600 α = 0.3126	ß Poisson model	(Haas et al., 1999, Labite et al., 2010, Seidu and Drechsel, 2010)
Ascaris	N_{50} =859 α = 0.104	ß Poisson model	(Navarro et al., 2009)
Norovirus	dose-response dataset of Teunis et al. (2008)	ß Poisson model	(Teunis et al., 2008)
Giardia	R = 0.0199	Exponential	(Rose et al., 1991)

5.5 QMRA-MC Simulation and Health impacts

Quantitative Microbial Risk Assessment (QMRA) models with 10,000 Monte Carlo simulations (MC-QMRA) based on the improved Karavarsamis-Hamilton method was used to estimate annual median risks of pathogen infections for different wastewater qualities under selected exposure scenarios[3]. Figure 5-1 shows the approach by which health impacts associated with alternative wastewater reuse strategies in terms of DALYs were estimated.

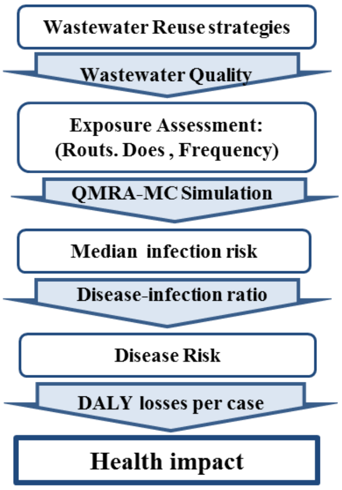

Figure 5-1 Estimating Health Impacts from alternative wastewater reuse strategies

5.5.1 Wastewater reuse strategies

The alternative wastewater reuse strategies that were evaluated in this study included different wastewater treatment options and post-treatment measures. The average pathogen reduction efficiencies of the various wastewater treatment options were selected and presented in Table 5-4. These typical performance parameters in terms of pathogen reduction were drawn from typical efficiencies cited in the literature (Table 5-3) and represent the likely average preformance of choosen treatment technologies (WHO, 2006, Jiménez et al., 2010b, Mara et al., 2010a, Keraita et al., 2010, Scheierling et al., 2010). While health protection for those working in the wastewater irrigated fields could be achieved by wastewater treatment only, in the case of unrestricted irrigation health protection of the consumer can only be achieved by a combination of both wastewater treatment and post-treatment health protection measures.

There are various options that can be applied to reduce pathogen numbers after wastewater treatment. The main post-treatment health protection control measures and their effectiveness

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[3] Simulations using QMRA: A Beginners Guide - Monte carlo simulation programmes, available at (the program is available at: http://www.personal.leeds.ac.uk/~cen6ddm/QMRAbeginners.html)

in pathogen reduction are listed in Table 5-5 (Mara and Kramer, 2008). As the fieldwork could not be carried in order to gather information related to farming practices in the case study farms, only drip irrigation was included as a post-treatment health protection control measure to reduce the health impact of the exposure to wastewater irrigation crops.

Table 5-3 Typical Pathogen reduction achieved by different wastewater treatment options considered in this study from the literature

	Treatment options	**Pathogen reduction (log units)**			
		bacteria	**Viruses**	**protozoan**	**Helminth Eggs**
	On-farm treatment				
1	Three tanks systems	1-2	1-2	1-2	1-3
2	Three tanks systems+ sand filter	2-4	2-4	2-4	1-4
	Treatment plants				
3	Convectional activated sludge	1-3	0-3	0-2	1-<2
4	Convectional activated sludge + disinfection (Chlorination)	3-6	1-5	0-2	1-2
5	Waste stabilisation bonds	1-6	1-4	1-4	1-3
6	Convectional activated sludge + advanced treatment (UF+RO)	>6	>6	>6	>3

Table 5-4 Parameters used for treatment options

Scenario	**Treatment options**	**Effectiveness of Treatment Pathogen reduction (log units)**			
		Salmonella	**Norovirus**	**Giardia**	**Ascaris Eggs**
	On-farm treatment				
1	Three tanks systems	1	1	1	1
2	Three tanks systems+ sand filter	3	3	3	3
	Treatment plants				
3	Convectional activated sludge	2	1	1	1
4	Convectional activated sludge + disinfection (Chlorination)	4	3	1	2
5	Waste stabilisation bonds	4	2	2	2
6	Convectional activated sludge + advanced treatment (UF+RO)	6	6	6	3

Table 5-5 Post-treatment health Protection Measures to Reduce Health Risks(Mara and Kramer, 2008)

On- farm Control measures	Pathogen reduction (log units)	Comments
drip irrigation	2	Included as it already common practice in the case study[4]
Overnight storage in baskets	0.5-1	Excluded due to lake of information on farming practices
Pathogen die-off	0.5-2 per day	Excluded due to lake of information on farming practices
Produce Washing	1	Excluded due to lake of information on farming practices
Produce Disinfection	2	Excluded due to lake of information on farming practices
Produce peeling	2	Excluded due to lake of information on farming practices

5.5.2 Acceptable additional risk and disease burden

Following the publication of the update to the WHO 2006 Guidelines, a maximum tolerable additional DALY loss of 10^{-4} per person per year was used in this study (Mara et al., 2010b). Using a tolerable additional DALY loss of 10^{-4} would be sufficient for health protection from wastewater exposure or the consumption of wastewater irrigated food.

The DALY loss per case of disease for Norovirus, Salmonella, and Giardia were adopted from the WHO estimates of the foodborne disease burden in 2010 in the Eastern Mediterranean Region (EMR) (Table 5-7) (Torgerson et al., 2015, Kirk et al., 2015). These values were similar or one order-of-magnitude higher than the values presented in many studies in the literature as it is shown in Table 5-8 this could be because values for DALY losses in most of these studies were based on data from developed countries.

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[4] Based on research knowledge of the case study and confirmet senior employee in Agriculture development committee. Ministry of agriculture and livestock in Misurata

DALY loss per case of Ascaris was estimated based on the information presented by (Havelaar and Melse, 2003). This method has been used in different studies in Ghana to quantify the health risks associated with pathogen exposure using quantitative microbial risk assessment (Lunani et al., 2007, Labite et al., 2010, Machdar et al., 2013, Barker et al., 2014). The major disease outcome from Ascaris infection was assumed to be a high intestinal obstruction (95% of cases) with the remaining 5% of the cases going on to develop contemporaneous cognitive deficit (Bundy et al., 2004). The severity weights and the mean duration were taken from Lopez et al., (2006), and Bundy et al. (2004) respectively. A mortality rate on average of 0.08% was used, and the mean age of death was assumed to be one year (Lunani et al., 2007, Labite et al., 2010, Machdar et al., 2013). The years of life lost following death from Ascaris was taken to be the life expectancy at birth of Libya (WHO, 2015) minus death at the age of 1 year (66 -1=65 years). The severity weight, duration, and disease burden, are shown in Table 5-6. The DALY losses per case presented in Table 5-6 are consistent with the literature and WHO estimates of the foodborne disease burden in 2010 in Eastern Mediterranean Region (EMR) (Torgerson et al., 2015).

Table 5-6 Severity, duration and disease burden per case for Ascaris for the case study

Outcomes	**Severity**	**Duration**	**Likelihood of outcome**	**Disease burden per case (DALYs)**
Intestinal obstruction, population	**0.024**	**35 days (0.1 years)**	**95%**	**2.3 x 10^{-3}**
Contemporaneous cognitive deficit	**0.006**	**28 days (0.08 years)**	**5%**	**2.4 x 10^{-5}**
Death	**1**	**65**	**0.08%**	**0.052**
TOTAL				**5.4 x 10^{-2}**

Table 5-7 DALY losses per case for key pathogens included in the study

Pathogen	**DALY losses per case of disease**
Norovirus	**1.2 x 10^{-2}**
Salmonella	**6.3 x 10^{-2}**
Ascaris	**5.4 x 10^{-2}**
Giardia spp	**1 x 10^{-3}**

Table 5-8 DALY losses per case of disease for key pathogens included in the study in the literature.

Pathogen	DALY losses per case of disease	Comment	Sources
Norovirus	9×10^{-3}	From study in Netherlands It used by (Mara and Sleigh, 2010b) to estimate of norovirus infection risks to urban farmers in developing countries using wastewater for crop irrigation	(Kemmeren et al., 2006)
	1.06×10^{-4} to 6.23×10^{-3}	Used by(Barker et al., 2014) to study the gastroenteritis risks associated with consumption of street food salads in Kumasi, Ghana	(Cressey and Lake, 2009, Haagsma et al., 2008, Kemmeren et al., 2006, Begg et al., 2007)
	3.71×10^{-4} to 6.23×10^{-3}	the average of this range of value ((3.3×10^{-3}) used by (Mok et al., 2014) estimate of norovirus infection risks from wastewater irrigation of vegetables in Shepparton, Australia	(Cressey and Lake, 2009, Kemmeren et al., 2006, Haagsma et al., 2008, Lake et al., 2010)
	1.2×10^{-2}	WHO Estimates of the Foodborne Disease Burden in 2010 in Eastern Mediterranean Region (EMR)	(Kirk et al., 2015)
Salmonella	1.9×10^{-2}	Based on study in Netherlands	(Kemmeren et al., 2006)
	6.7×10^{-2}	Based on study In Accra- Ghana A quantitative microbial risk assessment was applied to evaluate the microbial risks of the Urban Water System	(Labite et al., 2010)
	6.3×10^{-2}	adopted from WHO Estimates of the Foodborne Disease Burden in 2010 in Eastern Mediterranean Region (EMR)	(Kirk et al., 2015)
Ascaris	$8{\cdot}25\times 10^{-3}$	Used by (Mara and Sleigh, 2010b) to estimate of norovirus infection risks to urban farmers in developing countries using wastewater for crop irrigation	(Chan, 1997, Mara and Sleigh, 2010a)
	5×10^{-2}	Used by (Labite et al., 2010, Machdar et al., 2013) to evaluate health effects of urban water system of Accra, Ghana	(Lunani et al., 2007, Machdar et al., 2013, Labite et al., 2010)
	5.4×10^{-2}	Calculated for the case study based on (Havelaar and Melse, 2003, Machdar et al., 2013, Labite et al., 2010)	(Lunani et al., 2007, Machdar et al., 2013, Labite et al., 2010)
	5×10^{-2}	WHO Estimates of the Foodborne Disease Burden in 2010 in Eastern Mediterranean Region (EMR)	(Torgerson et al., 2015)
Giardia	(2.10×10^{-3} to 2.68×10^{-3})	Pathogen reduction requirements for direct potable reuse in Antarctica: Evaluating human health risks in small communities Originally adopted from to studies in Netherlands	(Barker et al., 2013) (Havelaar et al., 2012, Vijgen et al., 2007)
	1×10^{-3}	WHO Estimates of the Foodborne Disease Burden in 2010 in Eastern Mediterranean Region (EMR)	(Torgerson et al., 2015)

A Norovirus disease/infection ratio of 0.80 was used and this was based on information provided by (Moe, 2009) and agrees with the values that have been used by (Mara and Sleigh, 2010b) to estimate of norovirus infection risks to urban farmers in developing countries using wastewater for crop irrigation. For salmonella, a disease /infection ratio of 0.7 was used and this value was adopted from (WHO, 2006) which is the same disease /infection ratio used for the bacterial indicator Campylobacter.

As a worst-case scenario, it was decided that a disease/infection ratio of 1 would be used for Ascaris and Giardia which means that all those infected with Ascaris or Giardia with go on to develop Ascariasis and Giardiasis).

The maximum tolerable additional DALY loss of 10^{-4} per person per year is translated into tolerable infection risks using the following formulae and the results are shown in Table 5-9

$$\text{Tolerable disease risk pppy} = \frac{\textbf{Tolerable DALY loss pppy (i.e.,} \mathbf{10^{-4}}\textbf{)}}{\textbf{DALY loss per case of disease}} \qquad \text{Equation 5-3}$$

$$\text{Tolerable infection risk pppy} = \frac{\textbf{Tolerable disease risks pppy}}{\textbf{Disease/infection ratio}} \qquad \text{Equation 5-4}$$

Table 5-9 DALY losses, disease risks, disease/infection ratios and tolerable Infection risks for key pathogens included in the study

Pathogen	DALY losses per case of disease	Tolerable disease risks pppy equivalent to 10^{-4} DALY loss pppy	Disease/Infection ratios	Tolerable infection risks
Norovirus	1.2×10^{-2}	8.3×10^{-3}	0.8	1.04×10^{-2}
Salmonella	6.3×10^{-2}	1.6×10^{-3}	0.7	2.3×10^{-3}
Ascaris	5.4×10^{-2}	1.8×10^{-3}	1	1.8×10^{-3}
Giardia spp	1×10^{-3}	0.1	1	0.1

5.6 Results

5.6.1 MC-QMRA simulation result

For a tolerable DALY loss of $\leq 10^{-4}$ the corresponding tolerable infection risks for norovirus, salmonella, giardia and Ascaris are 1.04×10^{-2}, 2.3×10^{-3}, 0.1 and 1.8×10^{-3} pppy respectively as is given in Table 5-9.The results of the MC-QMRA simulation for unrestricted irrigation are given in Table 5-10 and Table 5-11 for several different wastewater qualities. From Table 5-10 it can be seen that the estimated norovirus median infection risk of ~ 10^{-3} pppy give a target wastewater quality of 10^2- 10^3 E. coli per 100 ml. Thus based on the typical raw wastewater quality (from Table 5-1) a total required reduction of 5 log unit is required to achieve the tolerable risks of 1.04×10^{-3} for norovirus infection. The table also shows that Salmonella and Giardia infection risks are lower than norovirus by three and two orders of magnitude, respectively. For Ascaris, Table 5-11 indicates that a 4-log unit reduction of Ascaris eggs results in an Ascariasis risk of 2.3 × 10^{-3} pppy which is not significantly higher than the tolerable risk of 1.8 x 10^{-3} pppy. Therefore, 4-log unit reduction of Ascaris eggs would be a sufficient for achieving the required health protection from an Ascariasis risk.

Table 5-10 Unrestricted irrigation Median infection risks from the consumption of 375 g of wastewater-irrigated tomatoes estimated by 10,000-trial Monte Carlo simulations*

Wastewater quality (E. coil per 100 ml)	Median infection risk pppy		
	Norovirus	Salmonella	Giardia
10^7- 10^8	1	0.22	0.67
10^6- 10^7	1	2.4 x 10^{-2}	0.1
10^5- 10^6	1	2.4 x 10^{-3}	1.1 x 10^{-2}
10^4- 10^5	0.58	2.4 x 10^{-4}	1.1 x 10^{-3}
10^3- 10^4	8.3 x 10^{-2}	2.4 x 10^{-5}	1.1 x 10^{-4}
10^2- 10^3	8.6 x 10^{-3}	2.4 x 10^{-6}	1.1 x 10^{-5}
10^1- 10^2	8.6 x 10^{-4}	2.4 x 10^{-7}	1.1 x 10^{-6}
1 - 10	8.6 x 10^{-5}	2.0 x 10^{-8}	1.1 x 10^{-7}

375g of raw tomato was eaten per person per 2 days; 3.5– 4 ml wastewater remaining on 375g tomato after irrigation; 0.1–1 norovirus and Salmonella per 10^5 e. Coli ; 0.01-0.1 Giardia per 10^5 e. Coli; and variation of 25% of pathogen coefficients. No pathogens die-off

Table 5-11 Unrestricted irrigation Median Ascaris infection risks from the consumption of 375 g of wastewater-irrigated tomatoes estimated by 10,000-trial Monte Carlo simulations*

Wastewater quality (eggs per Litter)	Median Ascaris infection risk pppy
10 – 100	1
1 -10	0.86
1	0.33
0.1 – 1	0.2
0.01 – 0.1	2.2 x 10^{-2}
0.001 - 0.01	2.3 x 10^{-3}
0.0001-0.001	2.3 x 10^{-4}
0.00001-0.0001	2.3 x 10^{-5}

375 g of raw tomato was eaten per person per 2 days; 3.5– 4 ml wastewater is remaining on 375 g tomato after irrigation; and variation of 25% of pathogen coefficients.

In the case of restricted irrigation, it can be seen from Table 5-12 that the tolerable norovirus infection risk of 1.04 x 10^{-2} pppy can be achieved by a 3-log unit reduction. The table also indicates that crop restriction could be sufficient to reduce the risks from salmonella and giardia infection and no additional log reduction is required to achieve tolerable infection risk of 2.3 x 10^{-3}, 0.1 for salmonella and giardia respectively. MC-QMRA simulation results for Ascaris in Table 5-13 shows that 1−10 eggs /litter results in an Ascaris infection risk of 7.3 x 10^{-3} pppy which is higher that than the tolerable Ascaris infection risk of 1.8 x 10^{-3} pppy. However, the results also show that the median infection risk is 1.3 x 10^{-3} for wastewater quality of 1 egg per litre which is lower than the tolerable Ascaris infection risk of determined above. Therefore, for restricted irrigation 1 log reduction of would be sufficient to achieve the acceptable, marginal health risk.

Table 5-12 Restricted irrigation Median infection risks from involuntary ingestion of 10-100 g wastewater-contaminated soil per day for 150 days per year estimated by 10,000-trial Monte Carlo simulations*

Soil quality (E. coil per 100 g)	**Median infection risk pppy**		
	Norovirus	**Salmonella**	**Giardia**
10^7- 10^8	1	2.9 x 10^{-3}	4.8 x 10^{-2}
10^6- 10^7	0.56	2.9 x 10^{-4}	4.9 x 10^{-3}
10^5- 10^6	9.9 x 10^{-2}	2.9 x 10^{-5}	4.9 x 10^{-4}
10^4- 10^5	1.0 x 10^{-2}	2.9 x 10^{-6}	4.9 x 10^{-5}
10^3- 10^4	1.0 x 10^{-3}	2.9 x 10^{-7}	4.9 x 10^{-6}
10^2- 10^3	1.1 x 10^{-4}	3.0 x 10^{-8}	5.0 x 10^{-7}
10-100	1.1 x 10^{-5}	3.0 x 10^{-9}	5.0 x 10^{-8}
1-10	1.1 x 10^{-6}	3.0 x 10^{-10}	5.0 x 10^{-9}

Assumptions: soil quality was taken(E. coli per 100 g), as the wastewater quality (E. coli per 100 ml), as a worst-case scenario; 0.1–1 norovirus and Salmonella per 10^5 e. Coli ; 0.01-0.1 Giardia per 10^5 e. Coli; and variation of 25% of pathogen coefficients. No pathogens die-off

Table 5-13 Restricted irrigation Median Ascaris infection risks from involuntary ingestion of 10-100 g wastewater-contaminated soil per day for 150 days per year estimated by 10,000-trial Monte Carlo simulations*

Soil quality (eggs per Kg soil)	**Median Ascaris infection risk pppy**
10 - 100	7.1 x 10^{-2}
1 -10	7.3 x 10^{-3}
1	1.3 x 10^{-3}
0.1 - 1	7.4 x 10^{-4}
0.01 - 0.1	7.4 x 10^{-5}
0.001-0.01	7.4 x 10^{-6}
0.0001-0.001	7.4 x 10^{-7}

Assumptions: soil quality (eggs per kg) taken, as the wastewater quality (eggs per liter) as a worst-case scenario.

Table 5-14 summarises the required pathogen reduction for each of the key pathogens in the cases of both restricted and unrestricted irrigation. It can be noted that although four reference pathogens: Norovirus, Salmonella, Giardia and Ascaris were chosen as the key organisms, the risks from salmonella and giardia seem to be of limited significance particularly for restricted irrigation compared to norovirus and Ascaris.

Table 5-14 Required Pathogen reduction and corresponded wastewater quality to achieve the maximum tolerable additional DALY loss of 10^{-4} per person per year

Pathogen	Unrestricted irrigation		Restricted irrigation	
	Required Pathogen reduction	**Wastewater quality**	**Required Pathogen reduction**	**Wastewater quality**
	(log units)	**E. coli /100 ml**	**(log units)**	**E. coli /100 ml**
Norovirus	5 log	10^2- 10^3	4 log	10^3- 10^4
Salmonella	2 log	10^5- 10^6	0	10^7- 10^8
Giardia	1 log	10^6- 10^7	0	10^7- 10^8
	(log units)	**eggs / litre**	**(log units)**	**eggs per litre**
Ascaris	4 log	10^{-3}- 10^{-2}	1 log	1- 10

5.6.2 Related Health Implications of Application of Treatment Options under Consideration

As it has been mentioned earlier the health risk from salmonella and giardia, seem to be of limited significance as a result of irrigation with wastewater, compared to norovirus and Ascaris. Therefore, for further assessment, only Norovirus and Ascaris were considered to assess and compare the effectiveness of the various proposed management options to reduce the health impacts as a result of irrigation with wastewater.

The health impact as a result of consuming wastewater irrigated crops (unrestricted irrigation) are shown in Table 5-15. All the treatment options presented in this table were combined with the application of wastewater using drip irrigation. Table 5-16 shows the impact on farmer’s health (restricted irrigation) as a result of exposure to wastewater effluent from different treatment options. Figure 5-2 compares the summary results of health impacts from both scenarios

The results indicate that apart from the three tank system all treatment options could result in more than 90% of Total DAYLs averted. However, the model results suggest that the effectiveness of activated sludge is highly dependent on effective and continuous chlorination, which is consistent with the information presented in the literature(Jiménez et al., 2010b, Evans and Iyer, 2012).

In addition, using an on-farm three tank system and sand filter could be as effective as conventional activated sludge with chlorination and more efficient than waste stabilisation in reducing the health impact for both scenarios.

Also, as it is shown in Figure 5-2, the positive health impact from advanced treatment does not vary significantly from the positive health impact of other treatment options such as on farm three tank system and sand filters especially when it is combined with farm-based measures.

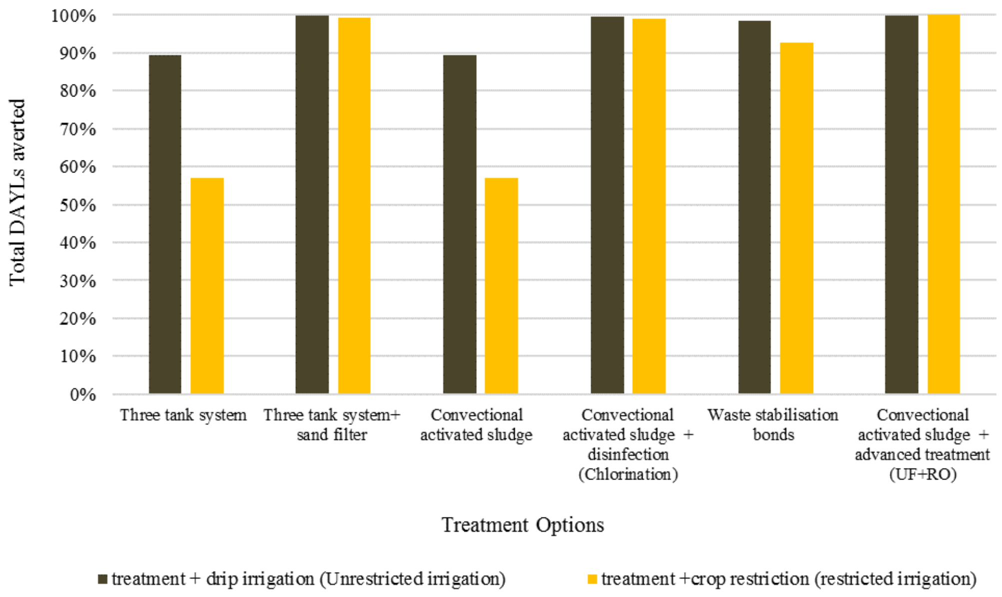


Figure 5-2 Comparisons between health impacts under restricted and unrestricted irrigation

5.7 Summary

This chapter was focused on estimating the health impacts of alternative wastewater reuse management strategies using Monte Carlo – Quantitative microbial risk analysis. Although Norovirus, Salmonella, Giardia and Ascaris were chosen as the reference pathogens, the results from the MC-QMRA indicated that the risks from salmonella and giardia are not significant compared to Norovirus and Ascaris.

The overall health impact results indicate that on-farm treatment options such as the three-tank system plus sand filter offer a more effective solution than conventional activated sludge systems. However, when disinfection is added to a conventional activated sludge system the performance is similar to the on-farm treatment systems (three tank system followed by sand filter).

Finally, the modelling results confirm that from a health perspective, for safe irrigation with wastewater, achieving the target microbial risk reduction does not necessarily require advanced treatment.

Table 5-15: Incidence of diseases and DALY burden under various treatment options for unrestricted irrigation

Treatment options	Raw WW	Three tank system	Three tank system+ sand filter	Conventional activated sludge	Convectional activated sludge + disinfection (Chlorination)	Waste stabilisation bonds	Conventional activated sludge + advanced treatment (UF+RO)
Median infection risk pppy							
Norovirus	1	0.58	8.6×10^{-3}	0.58	8.6×10^{-3}	8.6×10^{-2}	8.6×10^{-6}
Ascaris	1	2.2×10^{-2}	2.3×10^{-5}	2.2×10^{-2}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-4}
Disease Risk pppy							
Norovirus	0.8	0.464	6.9×10^{-3}	0.464	6.9×10^{-3}	6.9×10^{-2}	6.9×10^{-6}
Ascaris	1	2.2×10^{-2}	2.3×10^{-5}	2.2×10^{-2}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-5}
Disease incidence (cases per year)[*]							
Norovirus	120,000	69,600	1035	69,600	1035	10,350	1
Ascaris	150,000	3,300	3	3,300	345	345	3
TOTAL	270,000	72,900	1,038	72,900	1,380	10,695	4
Reduction	0.00%	73.00%	99.62%	73.00%	99.49%	96.04%	99.99%
DALYs (cases per year)[**]							
Norovirus	1,440	835	12	835	12	124	0
Ascaris	8,100	178	0	178	19	19	0
TOTAL	9,540	1,013	13	1,013	31	143	0
Reduction	0.00%	89.38%	99.87%	89.38%	99.67%	98.50%	100.00%

* Total exposed population is 150,000 person

** From Table 5-7 DALY loss per case of disease Norovirus 1.2 x 10-2, Ascaris 5.4 x 10-2

Table 5-16 Incidence of diseases and DALY burden under various treatment options for restricted irrigation

Treatment options	Raw WW	Three tank system	Three tank system+ sand filter	Conventional activated sludge	Conventional activated sludge + disinfection (Chlorination)	Waste stabilisation bonds	Conventional activated sludge + advanced treatment (UF+RO)
Disease Risk pppy							
Norovirus	0.8	0.448	8×10^{-3}	0.448	8×10^{-3}	7.9×10^{-2}	8.8×10^{-6}
Ascaris	7.1×10^{-2}	7.3×10^{-3}	7.4×10^{-5}	7.3×10^{-3}	7.4×10^{-4}	7.4×10^{-4}	7.4×10^{-8}
Disease incidence (cases per year)[*]							
Norovirus	2182	1222	22	1222	22	216	0
Ascaris	194	20	0	20	2	2	0
TOTAL	2376	1242	22	1242	24	218	0
Reduction	0.000%	47.727%	99.073%	47.727%	98.997%	90.845%	99.990%
DALYs (cases per year)[**]							
Norovirus	26	15	0	15	0	3	0
Ascaris	10	1	0	1	0	0	0
TOTAL	37	16	0	16	0	3	0
Reduction	0.000%	57.048%	99.256%	57.048%	98.988%	92.646%	99.992%

* Total exposed population is 3,656 person

** From Table 5-7 DALY loss per case of disease Norovirus 1.2 x 10-2, Ascaris 5.4 x 10-2

Chapter 6. Environmental risk assessment

6.1 Introduction

Despite the large body of work examining the health risks of wastewater reuse in agriculture. There are few studies that have attempted to quantify and compare associated environmental impacts as result of wastewater irrigation. In this chapter a novel approach for environmental risk assessment is developed; the general approach is first presented in (Elgallal et al., 2016). The developed model is relevant to arid and semi- arid areas in developing countries, in this chapter the model was applied to case study of Misurate in Libya to validated.

It is complicated and difficult to quantify the environmental risks arising from the chemical components of wastewater. The primary reason for this is the fact that tools or computer–based models similar to the ones developed for microbial risk assessment are not currently available, and therefore quantifying the environmental risks is more challenging. In this study qualitative analysis was carried out based on information in the literature to identify and rank these hazards based on the significance of their risks. The study only focuses on the most highly ranked hazards that could pose the most significant risks to the environment. These hazards were used as physicochemical indicators for evaluating different management strategies to reduce environmental impacts as a result of wastewater irrigation**.**

6.2 Hazard identification

Based on the literature review (chapter 2), Table 6-1 provides a summary of the main potential risks from chemicals as a result of irrigation with wastewater. The most serious water quality problems arising from wastewater reuse for irrigation are excessive levels of salt, heavy metals, excessive nutrients, and toxic organic compounds and emerging contaminants.

6.3 Environmental risk analysis

In general, the magnitude of chemical impacts and the likelihood depends on many factors including the chemical characteristics of the wastewater, effluent quality, and quantity, the availability of water sources, type and target yield, soil properties and condition, the vulnerability of aquifer, climate, and technology level and the social-economic conditions of farmers.

The case study is in arid and semi-arid regions where surface water is absent and rainfall is limited therefore the main receiving environments in concern would be soil, plants, and groundwater. Based on the literature and author experience of the case study, salinity and sodicity would be a significant environmental issue with respect to irrigation with wastewater. As a result of the high evaporation rate and the lack of rainfall, excessive salts are not naturally flushed out and accumulate in the soil profile causing soil salinity leading to serious environmental problems that contribute to a loss of soil productivity and fertility, and potential yield losses.

Excessive nitrogen supply can also be an important concern. Managing appropriate levels of nitrogen could be a challenging task particularly in developing countries where most irrigation rates are designed to match water requirements rather than nutrient requirements, and an oversupply of nitrogen may greatly affect the quality of crops and consequently reduce economic yields. Groundwater contamination from excessive levels of nitrate is a further area of concern in the case of using groundwater for drinking water supply.

Typically most domestic treated or partially treated wastewater has low levels of trace elements and usually within the permissible limits for irrigation water quality (Klay et al., 2010, Al Omron et al., 2012, Mohammad Rusan et al., 2007). Many studies has shown that soils have a high capacity to absorb and retain heavy metals and takes long term before causing any negative effects to groundwater and agricultural productivity or risking human health (from a few decades to a century depending on the type of effluent used) (Chen et al., 2013c, Smith et al., 1996, Tarchouna Gharbi et al., 2010). However, when the capacity of soil to retain heavy metals is reduced the metal enter a mobile phase, and may be released to groundwater or to be available to plant uptake (Sridhara Chary et al., 2008, Friedel et al., 2000).

The major concern with regard to the potential effects of heavy metals on agriculture production and human health would be related to the use of untreated wastewater or the use of bio-solids as fertilizers (Hamilton et al., 2007). Also, heavy metal would be a critical issue when industrial wastewater is used or blended with domestic wastewater and used for irrigation (Mapanda et al., 2005, Chen et al., 2013a, Toze, 2006a). Generally, health impacts associated with heavy metals transmission into the food chain are likely to arise long before they have a negative effect on the environment.

The potential adverse effects of exposure to emerging chemicals particularly EDCs have mainly been reported in aquatic environments (Qadir and Scott, 2010, Bolong et al., 2009, Toze, 2006a, Muñoz et al., 2009) and in animals in direct contact with polluted water (mainly surface water) (WHO, 2006, Toze, 2006a). Whilst the risks associated with emerging contaminants in treated wastewater used for irrigation are still controversial and not fully known, some studies have claimed that these contaminants are unlikely to pose a serious threat to groundwater, soil environments or human health as a result of its agricultural application (Chen et al., 2013a, Chen et al., 2011, WHO, 2006, Wu et al., 2014, Wu et al., 2015).

Nevertheless, there is a significant lack of studies concerning the prevalence and fate of emerging contaminants as a result of reusing wastewater for irrigation in terms of their potentially adverse effects on the terrestrial ecosystem, crop uptake and potential health impacts through the food-chain (Qadir and Scott, 2010, Muñoz et al., 2009, Chen et al., 2011, Fatta-Kassinos et al., 2011, Qin et al., 2015, Prosser and Sibley, 2015). Table 6-2 presents the assessment of the impacts and the likelihood of chemical pollutants from irrigation with wastewater.

Table 6-1 Potential environmental impacts associated with chemicals in wastewater used for irrigation

Hazard	**Impact**			
	Soil	**water**	**Crop**	
Excessive salts and specific ions:	Salinity and sodicity problems result in deterioration of soil structure Water-logging, Negative effects of hydraulic properties, Loss of soil productive capacity and fertility	groundwater quality deterioration	Affect plant growth through: • osmotic effects, • leaf burning, • plants nutrients deficiency, • phytotoxicity, • seedling emergence problems, • plant root growth restriction and • cropping difficulties	(Toze, 2006a, Leal et al., 2009, Muyen et al., 2011, Qadir and Scott, 2010, Malash et al., 2005, Hamilton et al., 2005, Qadir and Schubert, 2002, Rietz and Haynes, 2003, Friedel et al., 2000, Sou/Dakouré et al., 2013, García and Hernández, 1996
Metal : Cadmium Cd, Cobalt Co, Selenium Se, Molybdenum Mo, Manganese Mn, Zinc Zn, Boron B Copper Cu, Arsenic As, Mercury Hg, Lead Pd	Depending on PH, organic matter, and metals content metal can bind to soil particles and accumulate or mobilize. Once accumulated in soil removal can be difficult. Contamination can endure for hundreds of years due to long biological half-life. Negative impact on soil microbial biomass, microbial structure, microbial diversity, and bacterial abundance after long-term exposure	Leach form acid soil and /or highly permeable and shallow water table conditions. Contaminate groundwater and pose a risk to human health if it used for drinking purpose. Contaminate surface water and pose risk to aquatic life and can reach to human via food chine	Cd, Co, Se, and Mo due to their ability to bioaccumulation in Crops could lead to toxicity in human and animals Mn, Zn, B and Cu less strongly adsorbed by soil readily taken up by plants. Phytotoxic to plants at concentration before the concentration to be toxic to human. As, Hg, Leads Pd as strongly adsorbed by soil only can be uptake by plant root but not translocation to shoots Generally phytotoxic at high concentration	(Simmons et al., 2010, Mapanda et al., 2005, WHO, 2006, Zhang et al., 2008, Hamilton et al., 2005, Gwenzi and Munondo, 2008)
Excess nutrients :				

Hazard	**Impact**			
	Soil	**water**	**Crop**	
Nitrogen		Groundwater pollution and causing health problems mainly methemoglobinemia problems	Excessive vegetative growth, delay in maturity, Reducing crop size and quality, Low economic yield	(WHO, 2006, Hamilton et al., 2005, da Fonseca et al., 2007, Gwenzi and Munondo, 2008, Knobeloch et al., 2000, Chen et al., 2013a, Qadir and Scott, 2010)
Phosphorous		Eutrophication problems		
Toxic organic compounds & emerging contaminants	Adsorbed by soil particles and organic matter and accumulate in soil as result of long-term irrigation	Surface water pollution and affect aquatic ecosystems	Many can be uptake by plant or transferred to edible surface of crops via irrigation water or soil remain on the surface of crop	(Toze, 2006a, Chen et al., 2011, Qadir and Scott, 2010, Bolong et al., 2009, Muñoz et al., 2009, Luo et al., 2014, Wu et al., 2014, Chen et al., 2013a)

Table 6-2 Assessing the likelihood and the impacts and of chemical pollutants in irrigation with wastewater on related environments

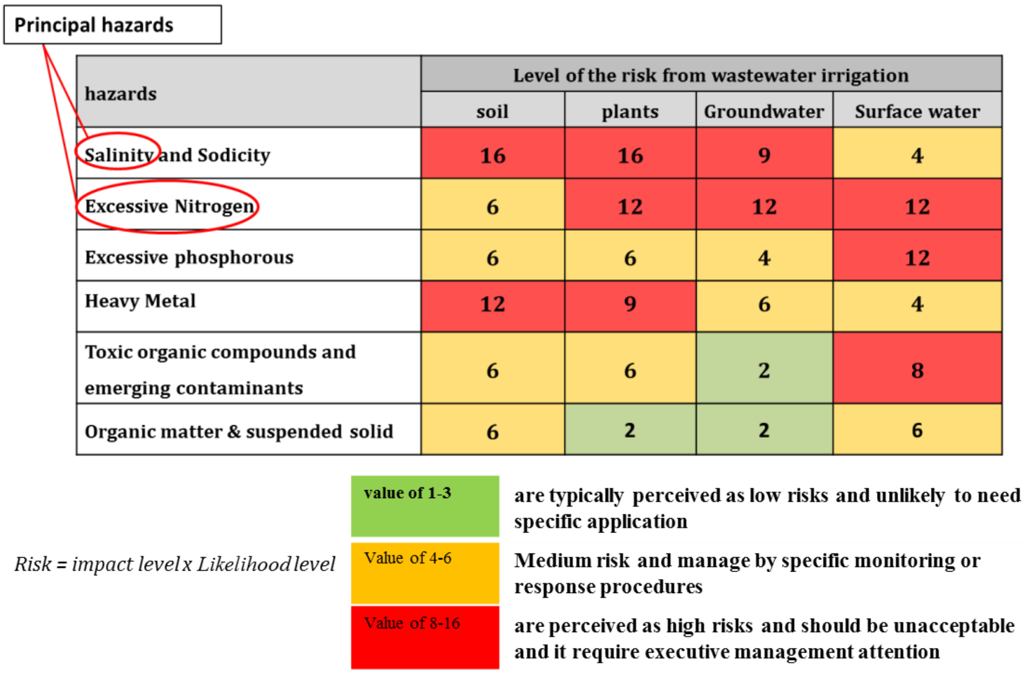
Hazards	soil		plants		Groundwater		Surface water	
	Likelihood	**Impact**	**Likelihood**	**Impact**	**Likelihood**	**Impact**	**Likelihood**	**Impact**
Salinity	Likely (4)	High (4)	Likely (4)	High (4)	Possible (3)	Medium (3)	Unlikely (2)	Low (2)
Excessive Nutrient								
• **nitrogen**	Possible (3)	Low (2)	Possible (3)	High (4)	Possible (3)	High (4)	Possible (3)	High (4)
• **Phosphorous**	Possible (3)	Low (2)	Possible (3)	Low (2)	Unlikely (2)	Low (2)	Possible (3)	High (4)
Heavy Metal	Possible (3)	High (4)	Possible (3)	Medium (3)	Possible (3)	Medium (3)	Unlikely (2)	Low (2)
Toxic organic compounds and emerging contaminants	Possible (3)	Low (2)	Possible (3)	Low (2)	Unlikely (2)	Negligible (1)	Unlikely (2)	High (4)
Organic matter & suspended solid	Possible (3)	Low (2)	Unlikely (2)	Negligible (1)	Unlikely (2)	Negligible (1)	Unlikely (2)	Medium (3)

6.4 Select principal hazard

The main purpose of risk evaluation is to rank the risks based on the outcomes of a risk analysis and identify which risks are most significant and require management during the development of wastewater reuse strategies for agriculture. In this study, risk evaluation involved comparing the level of risk (results from Impact level x Likelihood level) from table Table 6-2 with risk criteria established in the simple matrix shown in (Figure 4-6 chapter 4), the results are illustrated in Table 6-3. Based on the evaluation results in Table 6-3 it can be concluded that salinity and sodicity (with total score of 41) followed by excessive nitrogen supply (with total score of 36) are the most significant environmental risks from irrigation with wastewater in arid and semi-arid regions where surface water and rainfall are scarce. Heavy metals could be considered as a potential health risk rather than an environmental concern. However, their impacts on the environment or food chain are cumulative and are therefore likely to occur after long term application of wastewater (from a few decades to a century depending on the type of effluent used).

For the purposes of this study and due to time and data constrains, only salinity and excessive nitrogen were taken as the key physicochemical indicators for evaluating and assessing different management options to reduce environmental impacts as a result of irrigation with wastewater in arid and semi- arid climates.

Table 6-3 Rank of the risks from wastewater reuse in agriculture



Principal hazards

hazards	Level of the risk from wastewater irrigation			
	soil	plants	Groundwater	Surface water
Salinity and Sodicity	16	16	9	4
Excessive Nitrogen	6	12	12	12
Excessive phosphorous	6	6	4	12
Heavy Metal	12	9	6	4
Toxic organic compounds and emerging contaminants	6	6	2	8
Organic matter & suspended solid	6	2	2	6

Risk = impact level x Likelihood level

value of 1-3	are typically perceived as low risks and unlikely to need specific application
Value of 4-6	Medium risk and manage by specific monitoring or response procedures
Value of 8-16	are perceived as high risks and should be unacceptable and it require executive management attention

6.5 Assessment of Alternative Management Strategies

A heuristic approach using Excel was developed for assessing and comparing alternative wastewater management strategies to identify the most effective strategies for mitigating the risks due to salinity and excessive nitrogen while preserving the nutrient value. A set of appropriate representative wastewater management strategies were selected, considering their technological feasibility and potential for adaptation in the case study area. These strategies can be divided into wastewater treatment options and post-treatment measures (irrigation system and crops selection). Figure 6-1 illustrates the model flow chart for assessment of environmental risk management strategies.

6.5.1 Salinity management

Conventional wastewater treatment processes are inefficient for the removal of excessive salt and sodium (Bahri, 1998). Generally, salt removal requires advanced treatment such as reverse osmosis or cation exchange which are very expensive and may, therefore, be uneconomic for the production of water for irrigation (Qadir and Scott, 2010, Chen et al., 2013a, Toze, 2006a). Therefore, there is a need for specific inexpensive measures and management strategies to mitigate the impact ofsalinity. For the purposes of this research, in addition to wastewater treatment, the following management strategies were also considered:

- Regular application of water to transfer solutes through the soil profile and ensure the leaching of excess salt below the root zone.

- Crop selection based on a maximum leaching requirement of 25% (leaching requirement greater than 0.25–0.30 may not be practical because of the excessive amount of water required) (Ayers and Westcot, 1985)
- Blending with freshwater, if available, at specific ratios so ensure target salinities in the blended water are achieved.

Many studies have evaluated these approaches (Shalhevet, 1994, Oster, 1994, Shennan et al., 1995, Sharma and Rao, 1998, Maas and Grattan, 1999, Qadir and Oster, 2004, Malash et al., 2005, Corwin et al., 2007, Duan et al., 2011a) and it is anticipated that these approaches provide a good level of flexibility to suit different situations.

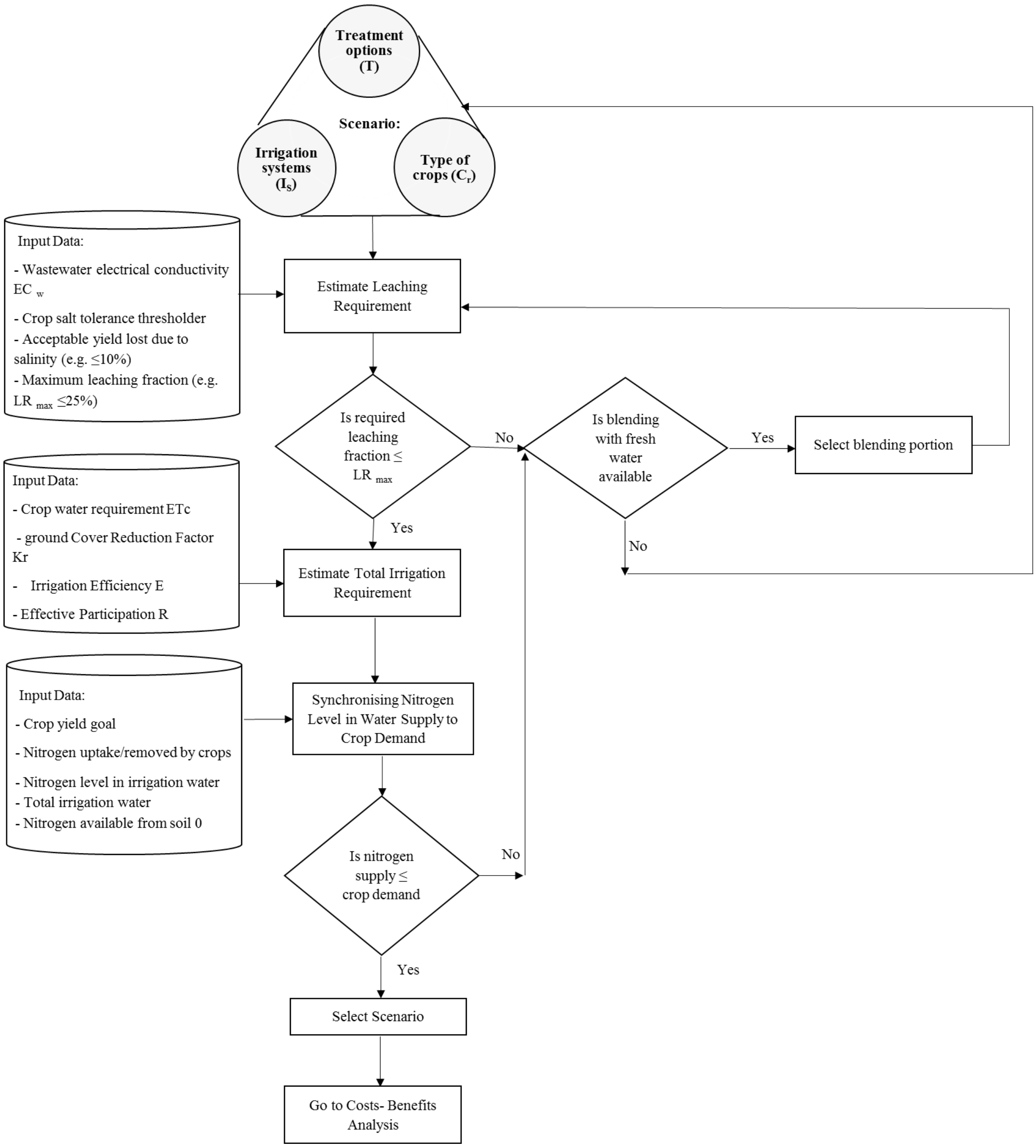


Figure 6-1 Flowchart for assessment of environmental risk management strategies

6.5.1.1 Procedure for calculating leaching fraction

Leaching requirement can be defined as the minimum fraction of the total irrigation water that must pass through the root zone for a particular quality of water to achieve maximum yield of a given crop (Letey et al., 2011, Minhas, 1996, Rhoades, 1974). Leaching requirement in this research was estimated using the traditional approach (Rhoades, 1974, Ayers and Westcot, 1985, Hoffman, 1985) which is widely used in the literature for the design and management of irrigation systems and wastewater land application (Hillel, 2000, Simmons et al., 2010, Minhas, 1996, Duan et al., 2011b, Hanson et al., 1999) . The approach assumed that steady-state conditions exist over long periods and are based on simple salt-balance concepts, with some modifications to account for salt precipitation and dissolution reactions. Therefore the minimum leaching fraction can be calculated using the following equations

Surface and sprinkle irrigation

$$\mathbf{LR}'_{\boldsymbol{Cr}} = \frac{\boldsymbol{ECw}}{[\mathbf{5}\boldsymbol{ECe}-\boldsymbol{ECw}]} \qquad \text{Equation 6-1}$$

Drip irrigation:

$$\boldsymbol{LR}_{\boldsymbol{Cr}} = \frac{\boldsymbol{ECw}}{\mathbf{2}\ \boldsymbol{x}\ [\boldsymbol{maxECe}]} \qquad \text{Equation 6-2}$$

Where:

- LR'_{Cr}= minimum leaching requirement fraction needed to control salts within the tolerance (ECe) of the crop (C_r)
- ECw = electrical conductivity of irrigation water (dS/m or mmhos/cm)
- ECe = electrical conductivity of saturated soil extract that tolerated by the crop (dS/m or mmhos/cm).It is recommended that the ECe value that can be expected to result in at least a 90% or greater yield be used in the calculation.
- maxECe = electrical conductivity of saturated soil extract that will reduce the crop yield to zero (dS/m or mmhos/cm)

The salt tolerance of a crop’s is the crop’s ability to endure the negative effects of excessive salt in the root zoon. Salt tolerance is defined more specifically as the extent to which yield of a crop is decreased when the crop is grown in a saline soil as compared to a non-saline soil. Salt tolerance is best described by models that relate the decrease in relative yields with the increase in soil salinity. Most crops can tolerate soil salinity up to a given threshold (maximum level) at which yield is not reduced (Ayers and Westcot, 1985, Hanson et al., 1999). The salt tolerance data that was used to calculate the leaching fraction, expressed as the electrical conductivity of saturated soil, was extracted from Maas and Grattan (1999) and based on the equation 6-3; the data is represented in (Table 6-4). These data provide a guide to relative tolerance in typical crops and assume that the soil is well drained, that leaching of 15% to 20

% is achieved, and that the soil is well drained. This latter assumption is made since the soils in the case study area are mostly sand soil to sandy loam, very low in nitrogen and organic matter content. This information is based on the researcher's own knowledge and confirmed by the literature (Al-Idrissi et al., 1996, Gerged, 2009).

$Y=100 - B\ (ECe - MinECe)$ Equation 6-3

Where:

- Y = Relative yield or yield potential (%)
- MinECe = Threshold value (dS/m) of root zone salinity at which 100% yield occurs
- B = Slope of linear line (% reduction in relative yield per increase in soil salinity, dS/m), and
- ECe = Average root zone soil salinity (dS/m).

Table 6-4 Salt tolerance threshold (Maas and Grattan, 1999)

Crops	Min Ece dS/m 100% yield	Max Ece dS/m 0% yield	slop%
wheat	6	20	7.1
barley	8	28	5
peas	3.4	13	10.6
broad beans	1.5	12	6.9
oat	5.2	20.4	6.6
potato	1.7	10	12
onion	1.2	7.4	16
lettuce and Green-Leaf Crops	1.3	9	13
carrot	1	8.1	14
Radish	1.2	8.9	13
Millets	6	18	8.3
tomato	2.5	13	9.9
water melon	2	7.8	17
cucumber	2.5	10	13
Aubergine	1.1	15.5	6.9
pepper	1.5	8.6	14
cauliflower	2.7	10.7	12.5
olive tree	4	12	12
palm tree	4	32	3.6
alfalfa	2	16	7.3

6.5.1.2 Procedure for calculating the total irrigation water requirement

Net irrigation requirement can be defined as the depth or volume of water that is required through the irrigation system to ensure the supply of full crop water requirement and leaching requirement excluding the contribution from other sources such as precipitation water stored in the soil, groundwater seepage, etc.

The net irrigation requirement does not include water losses (such as evaporation, wind drift, runoff, or deep percolation) during the process of conveyance and application to the field. Therefore, net irrigation water plus water losses and/or operational water constitute the Total Irrigation Requirement (TRc):

$\boldsymbol{TR_C} = (\frac{ETc}{E} - R)/(1- \mathbf{LR'_{Cr}})$ Equation 6-4

Where:

- ETc = crop water requirement per unit area (m^3/ha/Season)
- R = effective Precipitation
- E = Irrigation Efficiency

6.5.1.3 Crops water requirement

Usually, the water requirement of any crop is equal to the amount of water lost via evapotranspiration. Evapotranspiration will vary from crop to crop and will depend on climatic factors. It can be estimated based on local meteorological data using the following equation (Martin and Gilley, 1993):

$ETc = Kc. ETo$ Equation 6-5

Where:

- ETo = reference crop evapotranspiration
- Kc = is a crop factor.

For the purpose of this study, the water requirements of each crop (ETc) were extracted from a national study in Libya for estimating irrigation water requirements for the most common crops cultivated in different cities including our case study city.. the study used the CROPWAT software with Penman–Monteith equation to estimate ETc (Allen et al., 1998).

Typically, a well designed and installed irrigation system will not have any effect on ETc with the exception of drip irrigation systems. Since evapotranspiration includes plant transpiration and evaporation from the adjacent soil, the overall ETc would be expected to be less under drip irrigation as the irrigation is much more localised and therefore only a portion of soil around the plant is wetted. For drip irrigation systems, ETc is reduced accordingly using a ground cover reduction factor, Kr (Savva and Frenken, 2002). The ground cover reduction factor accounts for the amount of area the crop covers. The Kr used in this study was also extracted from the same study in Libya which was based on Vermeiren et al. (1980). However, if the crop is near or full groundcover, ETc will not be affected by drip irrigation (Savva and Frenken, 2002)

6.5.1.4 Effective Precipitation

Precipitation stored in the root zone could be effectively used for crop evapotranspiration and thus meet part of irrigation requirement. The contribution of precipitation to meet the evapotranspiration requirements may be insignificant in arid and semi- arid climates. However, the total consumptive use provided by precipitation was determined based on a frequency distribution of effective precipitation (Martin and Gilley, 1993). Table 6-5 provides an overview of the input data for crops water requirement which take into account effective rain.

6.5.1.5 Irrigation efficiency

Irrigation efficiency is an important element in the calculation of the total irrigation requirement. Irrigation efficiency is affected by the uniformity of water distribution and water loss during transportation and application caused by evaporation, wind drift, seepage, improper management (often poor irrigation scheduling), and runoff (Martin and Gilley, 1993). Irrigation efficiency varies from one location to another and it is a function of the irrigation method used, the physical condition of the irrigation system, soil condition, crop type, irrigation water management, timing and amount of irrigation water applied and climate conditions (Martin and Gilley, 1993). The following efficiencies were used in the present study and are taken from Martin and Gilley (1993).

- Sprinkle: 70%
- Drip: 90%

Table 6-5 Crop water requirement input data[1]**.**

Crops	**Crop Water Requirement ET_c**			
	Annual crop m3/ha/year	**fall- winter season (September to February) m3/ha/Season**	**spring-summer season (March to August) m3/ha/Season**	**Ground cover reduction factor of ETc (Kr)**
wheat	-	4940	-	-
barley	-	3610	-	-
peas*	-	3240	-	1
broad beans*	-	3230	-	1
oat	-	3040	-	1
potato	-	3920	-	1
onion	-	3910	5410	1
lettuce and Green-Leaf Crops	-	4520	3060	1
carrot	-	1900	3860	1
Radish	-	930	1220	1
Millets	-	-	4920	-
tomato	-	-	5790	1
water melon	-	-	6850	1
cucumber	-	-	3910	1
Aubergine	-	-	7890	1
pepper	-	-	7690	1
cauliflower	-	-	4350	1
olive tree	6580	-	-	0.8
palm tree	12980	-	-	0.8
alfalfa*	12190	-	-	-

[1] Source: General water authority (middle region), 2000, Irrigation *Water Requirement For The Most Common Crops Cultivated in Libya*.

6.5.2 Excessive Nitrogen management measures

Figure 6.2 shows some of the mitigation measures that can be used to control the adverse effects of excessive nitrogen from irrigation with wastewater. These include various wastewater treatments options, matching the nitrogen supply to the crops demand and also crop selection.

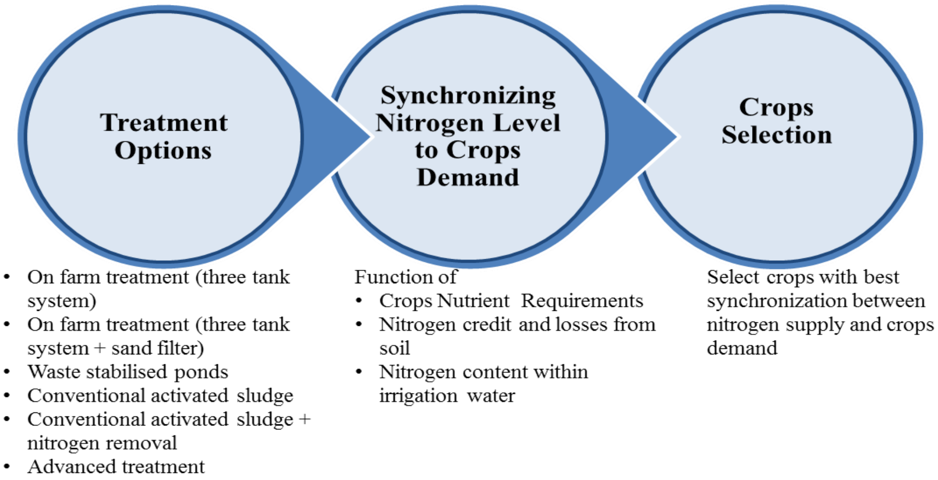


Figure 6-2 Nitrogen management options

6.5.2.1 Wastewater Treatment options

Various options are available to treat wastewater and produce a range of different effluent qualities. In the current study, a range of alternative wastewater treatment options have been selected to represent primary, secondary and advanced treatment. These treatments are on-farm treatment (three tank systems and sand filter) and wastewater treatment processes (conventional activated sludge with disinfection, waste stabilized ponds, conventional activated sludge with biological nitrogen removal and disinfection, and advanced treatment). Table 6.6 shows the expected effluent quality from each of the different treatments options and this data was drawn from typical treatment efficiency data presented in the literature (Table 6-7). These efficiencies were selected to represent the average performance of chosen treatment technologies for nitrogen and phosphorous removal. This data was used as input data in this study, however it important to mention that due to a lack of data about the nutrient removal efficiency of the three-tank system. The removal efficiency was based on the system will provide removal efficiency similar to primary sedimentation.

6.5.2.2 Synchronizing nitrogen application rates to the crops demand

Nitrogen (N) is the motor of plant growth. It constitutes 1 to 4% of dry matter of the plant. For most non-legume crops, plants absorb nitrogen from the soil in the form of either nitrate (NO_3^-) or ammonium (NH_4^+) (FAO, 2000, Rosen and Eliason, 2005, Roy et al., 2006). However, most crops have a limit to the amount of nitrogen that can be taken up by plants. Generally, sensitive crops may be affected by nitrogen concentrations above 5 mg/l, most other crops are relatively less affected until nitrogen exceeds 30 mg/l(Ayers and Westcot, 1985).In addition, nitrogen in the soil is subjected to many losses including nitrogen loss through ammonia volatilization, denitrification, mineralisation, leaching etc (figure 6-3 Nitrogen cycle). Only around 50% of nitrogen applied to crops actual uptake by crops (Bouwer and Idelovitch, 1987, GIZ, 2006, Bouwer and Chaney, 1974). Furthermore, in most soils ammonium is quickly converted to the nitrate form through nitrification and this nitrate form highly mobilized in the soil, therefore, managing the amount of nitrogen applied through irrigation water is more critical that the amount of water from a production and environmental standpoint (Rosen and Eliason, 2005).

Table 6-6 Wastewater qualities input data

Treatment option	Effluent quality	
	NO_3-N+ NH_4-N mg/l	TP-P
Raw wastewater	45	10
Effluent from septic tank	60	13
Septic tank +On farm (Three-tank system)	45	10
Septic tank +On farm (Three-tank system +sand Filter)	25	8.5
Septic tank + WSP	21	6.5
Sewerage +(WSP)	15	5
(Conventional activated sludge)	25	7
Activated sludge+ Biological Nitrogen Removal	8	7
Activated sludge+ ultrafiltration+ reverse osmosis	1	0.5

Table 6-7 Average effluent concentrations and typical removal efficiencies of the element of interest in different wastewater treatment process and literature sources from which relevant data have been extracted.

Treatment options	Average quality of the effluent mg/l				Average of removal efficiency%			Reference
	Ammonia –N	NO_3-N	TN	TP-P	TN	Ammonia –N	TP-P	
Raw wastewater	20-45	0-trac	20-70	4-15	n/a	n/a	n/a	(Tchobanoglous et al., 1991, Carey and Migliaccio, 2009, Metcalf et al., 2010, Sperling and de Lemos Chernicharo, 2005, Wu et al., 2009)
Wastewater from individual residence*	7-40	<1	31-80	6-17	n/a	n/a	n/a	(Tchobanoglous et al., 1991)
(septic tank)	20-60	<1	25-60	-	10-30	-	-	(Tchobanoglous et al., 1991, Sperling and de Lemos Chernicharo, 2005)
septic tank + sand Filtration	<5	20-30	-	-	40-70	70-90 *(nitrification)*	20-50	(USEPA, 1999, Tchobanoglous et al., 1991, Kuffour et al., 2009, Sperling and de Lemos Chernicharo, 2005)
Wastewater Stabilization pond (WSP)	10-15	-	15-20	-	50-80	60-80	>50	(Sperling and de Lemos Chernicharo, 2005, Peña and Mara, 2004)
Conventional activated sludge+ disinfection	1–10	10-30	15-35		<60	>80	25-35	(Tchobanoglous et al., 1991, Carey and Migliaccio, 2009, Metcalf et al., 2010, Sperling and de Lemos Chernicharo, 2005, Wu et al., 2009)
Activated sludge+ Biological Nitrogen Removal + disinfection	1-3	3-8	3-8		-	>80	25-35	(Tchobanoglous et al., 1991, Carey and Migliaccio, 2009, Metcalf et al., 2010, Sperling and de Lemos Chernicharo, 2005, Wu et al., 2009)
Activated sludge+ ultrafiltration+ reverse osmosis	≤0.1	≤1	≤1	≤0.5	-	99	95	(Wu et al., 2009, Carey and Migliaccio, 2009)

n/a: not applicable; *The typical characteristics of Wastewater from individual residence based on the flow of (200 l/capita/d)

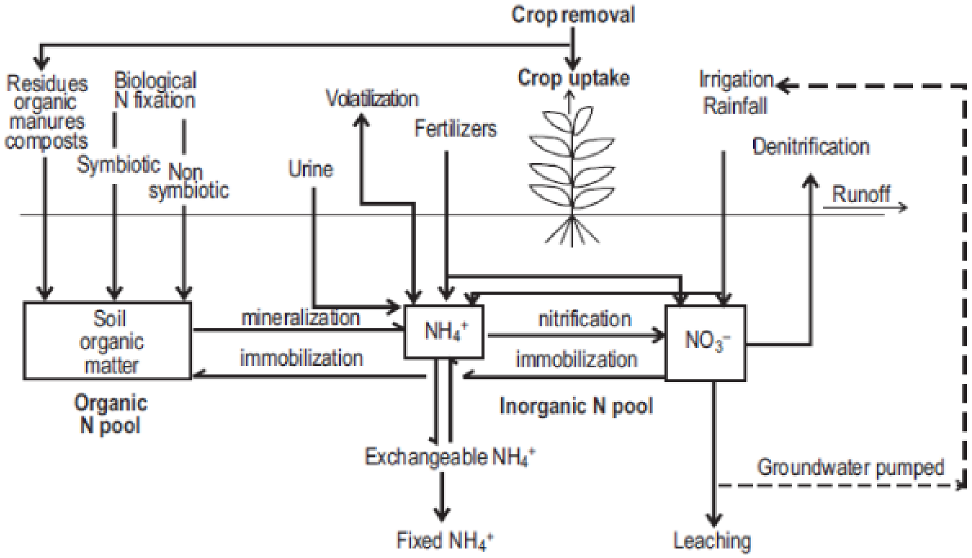


Figure 6-3 Nitrogen cycle*(Roy et al., 2006)*

Ideally, selecting effective nitrogen (and other nutrients) management approach could be achieved by using a mass-balance approach. A mass-balance approach for nitrogen management includes consideration of nitrogen available to crops within the soil; nitrogen losses due to ammonia volatilization and/or denitrification ,and mineralisation; nitrogen content within the irrigation water; and nitrogen uptake /removed by crop(Cassman et al., 2002, FAO, 2000, Olfs et al., 2005, Janssen et al., 2005) . This is could be challenging due to many reasons including (Richards et al., 2011, Cassman et al., 2002, Roy et al., 2006) :

- Actual uptake and removal are affected by soil and climatic conditions and it varies with crop yield, soil fertility and from year to year; hence accurate removal values can only be determined by laboratory analysis
- Nitrogen availability from soil varies seasonally and with climate and cropping pattern.
- Require knowledge of the site-specific factors that may affect nitrogen transformations and availability.
- The sensitivity of crops varies with the growth stages as well. High nitrogen levels can be beneficial in the beginning of growth stages while during the later flowering and fruiting stages excessive application may cause yield losses.
- Another difficulty related to the efficient use of nitrogen in the effluent as fertilizer is that the water demand and the nitrogen demand are not parallel.

However, it is possible to develop “approximate N budgets to evaluate „what if‟ scenarios by estimating typical crop yields in study area, typical values of nutrient Crop uptake/removal under study areas conditions for different crops; and predicting nitrogen credit and losses from soil based on data records of soils test and cropping systems. Typically for optimum management situation:

- crops nitrogen (uptake/removed) = nitrogen in the soils+ nitrogen in wastewater- nitrogen loss by (ammonia volatilization, denitrification, mineralisation)
- If crops nitrogen (uptake/removed)> (nitrogen in the soils+ nitrogen in wastewater- nitrogen loss by ammonia volatilization/denitrification, mineralisation), then chemical fertiliser is needed
- If crops nitrogen (uptake/removed) < (nitrogen in the soils+ nitrogen in wastewater- nitrogen loss by ammonia volatilization/denitrification, mineralisation). There is a potential risk from excessive nitrogen.

It must be emphasized that the calculations were based on several simplifications:

1. Total water and nutrients requirement will be compared with total water and nutrients supply for each season and do not take into account the variation of water and nutrients requirement during growing stages.

2. The ranges in nutrient Crop uptake/removal are based on typical nutrient concentrations and yields for good growing conditions.

3. As soil test records for estimating the nitrogen (or nutrient in general) that are available to plant is lacking in the case study, the calculation was conducted for two scenarios:
    - 50% of nitrogen in wastewater assumed to be not available to the plant due to nitrogen losses (which is the same assumption used to estimated nitrogen fertiliser in costs and benefits analysis as worst case scenario).
    - 25% of nitrogen in wastewater assumed to be not available to the plant due to nitrogen losses mainly from ammonia volatilization/ and denitrification.

However, results from soil test records -to estimate soil fertility and potential nitrogen losses- can be easily incorporated into the model when it is available.

Thus the outcome results only provide a broad indication for comparing and prioritizing agricultural activities and wastewater management strategies

6.5.2.3 Calculating crops’ nitrogen requirement

In general, different crops require different amounts of nutrients, the requirements for optimal nutrition depends largely on the type of crops and target yields (Roy et al., 2006). The common approach to determine crops nitrogen demand based on target yield the nitrogen uptake of the crop, Therefore:

Crops nitrogen requirement =crops nitrogen removal× crop yields

Searching for the most appropriate crops uptake and removal values are time-consuming and even confusing. The literature provides a relatively wide range of typical nutrients uptake and removal values by medium and good yields of some of the world’s crops, these values depending on yields, soil conditions climate and other factors (FAO, 2000, Roy et al., 2006, Wichmann, 1992, IPNI, 2015) . However, most of this estimation take into account the nutrients removed with the harvest portion and do not consider roots and above ground biomass. For that reason, most crops uptake values used in this study were taken from IFA recommendations(Wichmann, 1992) as they are relatively high. Wichmann (1992) provides a comprehensive estimation of nutrients uptake/removal values for more than 40 types of crops and vegetables that are widely growth in Tropical, Subtropical, and temperate regions. Table 6-8 gives the input data for crop nutrient uptake.

6.5.2.4 Crop yield

Estimating the target crop yields is important to estimate crops nutrient requirements. Underestimating crops yield could lead to underestimating fertiliser requirement, and consequently reducing the total crops production. Overestimating could lead to excessive nutrient supplied to crops. Typically target yields can be predicted from the historical record of crops yields in the study area. As data from the case study is limited, typical values from (Wichmann, 1992)world fertilizer use manual and other resources have been used. Table 6-9 provides Crops yields data

Table 6-8 Crops nutrients uptake (Wichmann, 1992)

Crops	N Kg/ton	P_2O_5 kg/ton	K_2O kg/ton
wheat	13.6	4	18.4
barley	11	4.6	18
peas*	0	11.17	32.5
broad beans*	0	14	31
oat	14	5.1	24
potato	5	0.8	6.7
onion	2.5	1	2.7
lettuce and Green-Leaf Crops	3.8	1.2	7.2
carrot	2.9	1.7	4.1
Radish	14.5	4.7	20.5
Millets	35.7	10.2	28
tomato	6	1.7	11
watermelon	3.7	1.1	6.7
cucumber	2	1.4	3.5
Aubergine	5.2	1.2	8.5
pepper	3.3	0.79	4.4
cauliflower	5.3	1.8	8
olive tree[1]	6.8	1.8	13
palm tree[2]	3.2	0.92	7.8
alfalfa*	20	9	37

* Legumes such as alfalfa, peas, and broad beans take most of her nitrogen from the air

Table 6-9 Crop yield input data

Crops	Target Marketable Yields (ton/ha) [1]	Yield (ton/ha) [2] In Case Study	Input data ton/ha
Fodder:			
alfalfa	15/year	15.6	**15**
oat	5 (grain) 9.8T DM	3.2 hay 7.5 grain	**9.8**
Grains:			
wheat	6.7 grain 13.7 TDM	2 Hay 4 grain	**13.7**
Barley (winter)	6.8 grain 11 TDM	2.5hay 5.6 grain	**11**
Millets	-	1.2 grain	**1.2**
Vegetable:			
beas	6	1	**6**
broad beans	5	2	**5**
onion	30 - 45	16	**30**
lettuce and Green-Leaf Crops	30 - 34	10	**30**
tomato	27-37	55	**27**
carrot	25-37	10	**25**
water melon	15 - 30	20	**15**
potato	30	75	**30**
cucumber	13-30	5	**13**
Aubergine	14-30	10	**14**
pepper	11 - 25	15	**11**
cauliflower	10-40	10	**10**
Radish	20-30	10	**20**
Tree:			
Palm tree	-	12	**12**
Olive tree	2.3[3]	4.5	**2.3**

1. (Wichmann, 1992)
2. This data based on Consulting a farmer from the case study, these values used as a guild to select target yield from IFA1992
3. (Boulal et al., 2013)

6.6 Results

6.6.1 Effective options for Salinity Management

From chapter 4 raw wastewater in the case study had a high salinity hazard (EC w= 4 dS/m) which is higher than the limit recommended by FAO for water quality used for irrigation (EC w= 3 dS/m)(Ayers and Westcot, 1985). Since the salinity of municipal water supply in the case study do not exceed 1.25 dS/m the increase of salinity in wastewater could be due to very saline ground water infiltration in sewerage system and illegal connection from small industry[5], in addition, other sources such as detergents and washing material, food and chemicals used during the treatment process. The results of the assessment of alternative salinity management strategies are presented in Table 6-10 and Figure 6-4. Where Table 6-10 provide a comparison of leaching requirement under conventional (including on-farm options) and advanced treatment using sprinkle and drip irrigation system, while Figure 6-4 shows total irrigation water requirement for selected crops under conventional and advanced treatment using sprinkle and drip irrigation system. As it has been mentioned earlier wastewater treatment processes are inherently inefficient for the removal of excessive salt. Therefore, it is necessary to combine conventional treatment with advanced treatment. However, in the absence of advanced treatment, Salinity managed by effective leaching of the root zone becomes more important under conditions where irrigation water and/or soil contain a high concentration of salts. Leaching requirements and their frequency generally depend on the salinity status in water or soil, salt tolerance of the crop, and irrigation methods. in our case study, a regular application of effective leaching with maximum 10% of acceptable yield loss due to salinity were applied, and crop selection was based on max leaching fraction of 25%.

Although using wastewater for irrigation in conjunction with freshwater, through blending improves the quality irrigation water, blending option was not available due to the extreme scarcity of water in this area. It is apparent from Table 6-10 and Figure 6-4 that under conventional treatment, apart from fruit tree and grains, leaching requirement excessed 25% for all crops when irrigation water applied by sprinkler systems, and in some case (such as root crops) leaching requirement can reach to 4 times crop water requirement to leach salt under root zone.

In contrast, the use of drip irrigation systems provides more advantages in using saline water. It allows a wider range of crops to be irrigated with such saline water; under drip irrigation (excluding field crops as practically difficult to irrigated with drip system) leaching

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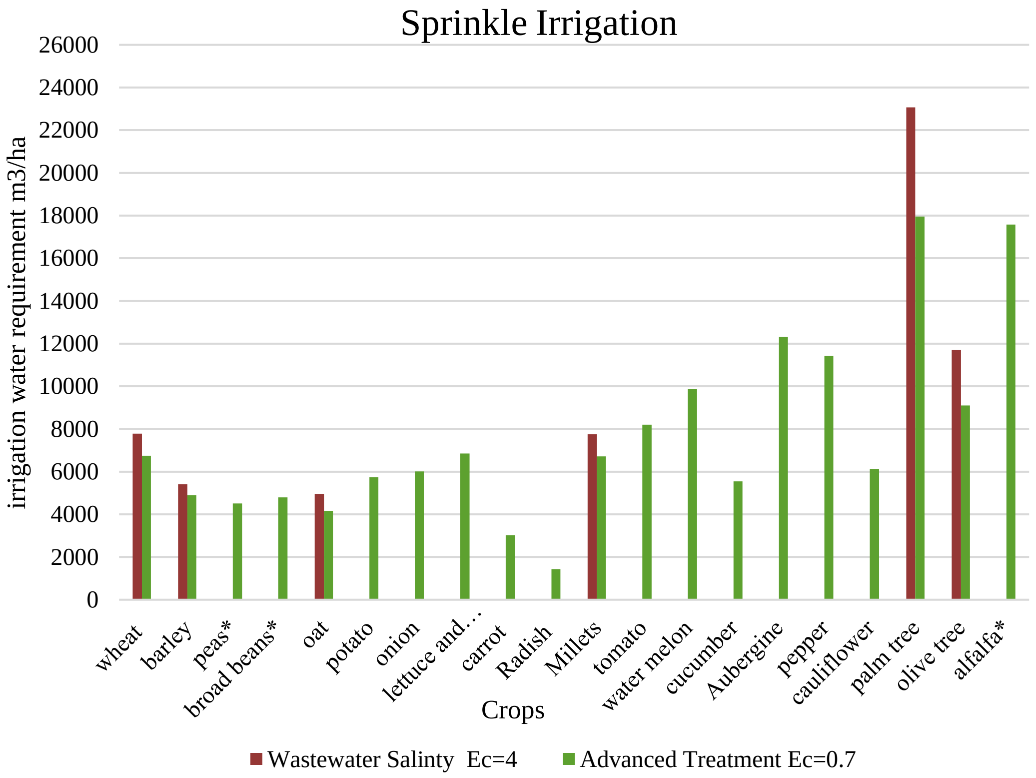
[5] General Water and Sewage Company Misurata- Libya

requirement for most of the crops range from 15% to 25%. This is because drip irrigation system maintains high soil potential and minimise salt accumulation in the wetting zone and subsequently maintaining a low salinity level in the root zone(Pescod, 1992).

Table 6-10 Leaching requirement under conventional and advanced treatment using sprinkle and drip irrigation system (Max leaching fraction 25%)

crops	Sprinkle Irrigation				Drip Irrigation			
	Wastewater Salinty		Advanced Treatment		Wastewater Salinty Ec=4		Advanced Treatment	
	LR%	TR m3/ha	LR%	TR m3/ha	LR%	TR m3/ha	LR%	TR m3/ha
wheat	15.38%	7784.24	2.39%	6747.88	-	-	-	-
barley	11.11%	5415.00	1.78%	4900.62	-	-	-	-
peas*	30.77%		4.29%	4513.85	15.38%	4254.55	2.69%	3699.60
broad beans*	114.29%		10.29%	4800.87	16.67%	4306.67	2.92%	3696.71
oat	18.18%	4954.07	2.77%	4168.67	-	-	-	-
potato	88.89%		8.97%	5741.97	20.00%	5444.44	3.50%	4513.53
onion	200.00%		13.21%	6006.67	27.03%		4.73%	4560.13
lettuce and Green-Leaf Crops	160.00%		12.07%	6853.86	22.22%	6457.14	3.89%	5225.43
carrot	400.00%		16.28%	3025.93	24.69%	2803.28	4.32%	2206.45
Radish	200.00%		13.21%	1428.70	22.47%	1332.85	3.93%	1075.63
Millets	15.38%	7752.73	2.39%	6720.56	-	-	-	-
tomato	47.06%		5.93%	8206.85	15.38%	7603.03	2.69%	6611.33
water melon	66.67%		7.53%	9876.74	25.64%		4.49%	7968.68
cucumber	47.06%		5.93%	5542.10	20.00%	5430.56	3.50%	4502.01
Aubergine	266.67%		14.58%	12316.10	12.90%	10065.43	2.26%	8969.20
pepper	114.29%		10.29%	11429.95	23.26%	11133.67	4.07%	8906.94
cauliflower	42.11%		5.47%	6135.54	18.69%	5944.44	3.27%	4996.78
palm tree	25.00%	23075.56	3.63%	17957.99	6.25%	15383.70	1.09%	14581.71
olive tree	25.00%	11697.78	3.63%	9103.51	16.67%	7018.67	2.92%	6024.61
alfalfa*	66.67%		7.53%	17576.28	-	-	-	-



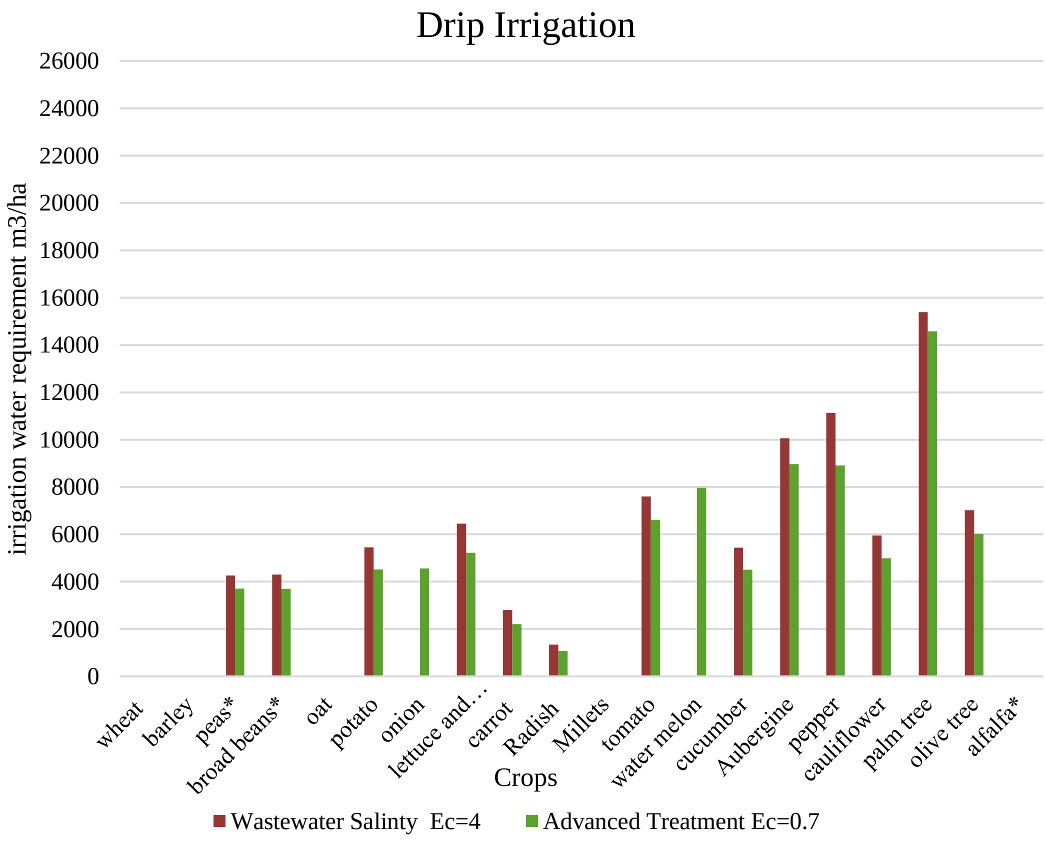


Figure 6-4 Total Irrigation Water Requirement for Selected Crops Under Conventional and Advance Treatment Using Sprinkle and Drip Irrigation System

6.6.2 Effective nitrogen management

To estimate the relative effect of different nitrogen management strategies, the model estimated nitrogen mass balance under two scenarios (50% and 25% of nitrogen lost from applied wastewater). The relative effect of each management strategy under the selected scenarios presented in Figure 6-5, Figure 6-6, Figure 6-7and Figure 6-8. The comparison of the results shows that apart from on- farm treatment option the overall efficiency of managing excessive nitrogen do not vary significantly under both scenarios for all treatment options. From Figure 6-5 and Figure 6-6 estimates of nitrogen losses have great impacts on the performance of on-farm treatment options.

Based on the results it is a clear that advanced and tertiary wastewater treatment are the most effective nitrogen management strategy to eradicate any potential impacts from nitrogen in wastewater used for irrigation. However, for reducing the potential impact from excessive nitrogen while preserving the fertiliser value in wastewater, the results suggest that waste stabilised ponds may be the best option.

It also apparent from the results that in the case of the use of waste stabilised ponds, activated sludge, or on-farm three tank system with sand filter, managing the excessive or unbalanced addition of nitrogen requires selecting crops that can take advantage of the high level of nitrogen such as grains, leafy crops, root crops, tomato, and potato.

The results also indicate that on farm three tank system may not be efficient to eliminate nitrogen in wastewater; under three tank system even when crop selection is considered there is a very limited range of crop could be considered.

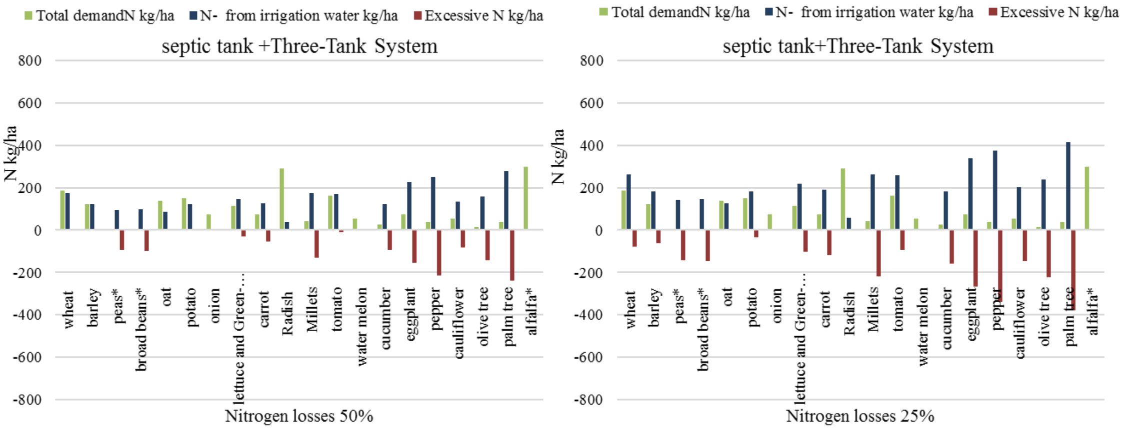
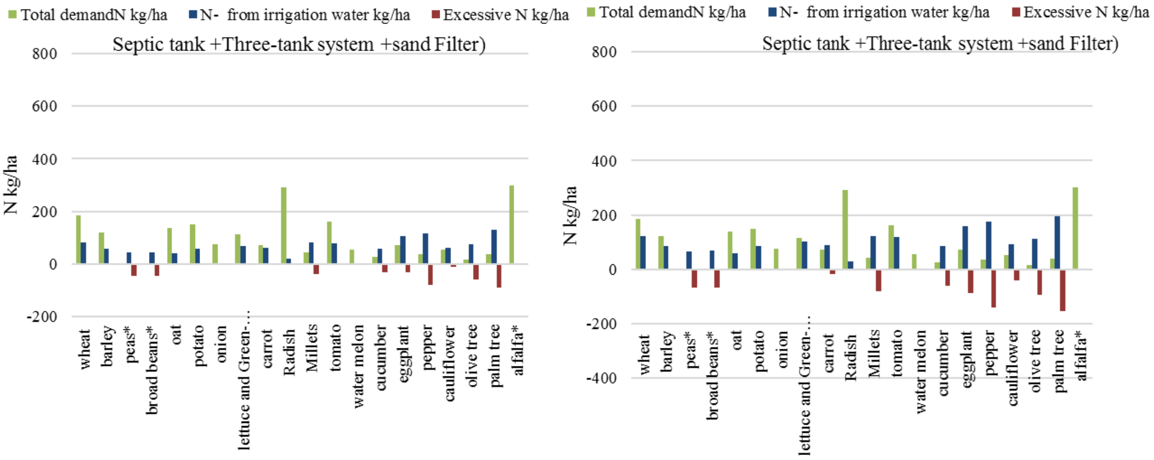


Figure 6-5 The effectiveness of on-site treatment options (Three tanks system) under 50% and 25% of nitrogen losses



a) Nitrogen losses 50%

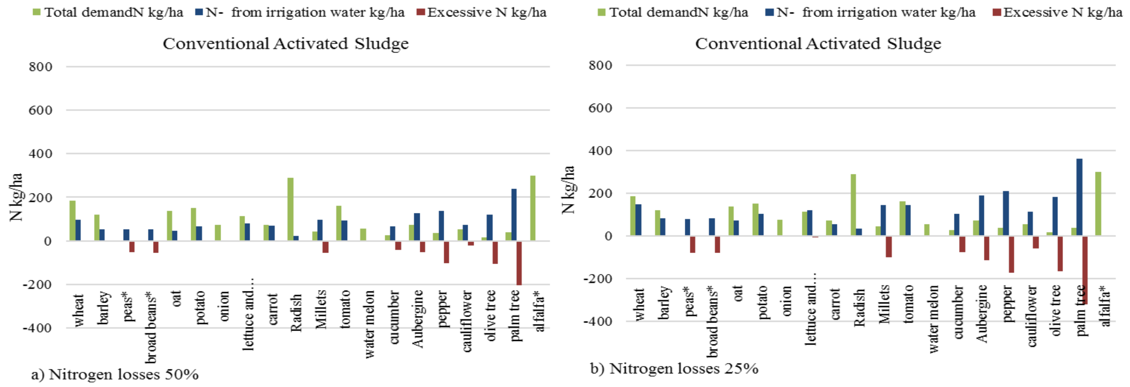
b) Nitrogen losses 25%

Figure 6-6 The effectiveness of on-site treatment options (Three tanks system+ sand filter) under 50% and 25% of nitrogen losses

a) Nitrogen losses 50%

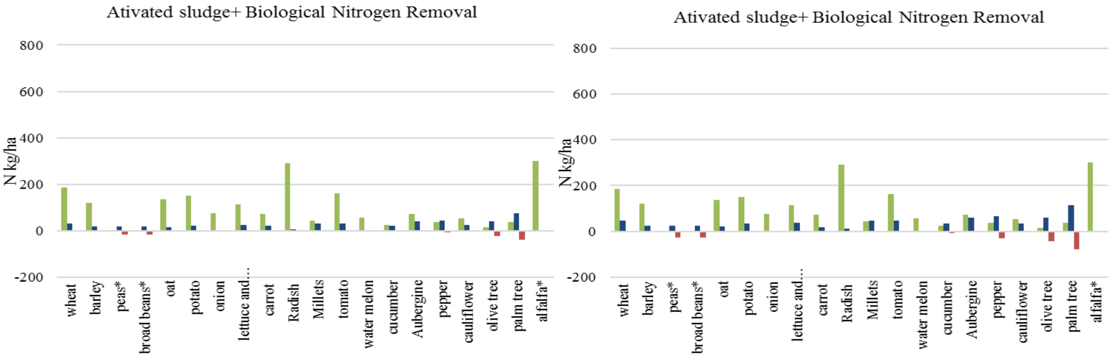
b) Nitrogen losses 25%

Figure 6-7 Comparisons of the effectiveness of waste stabilisation ponds (WSP) under 50% and 25% of nitrogen losses



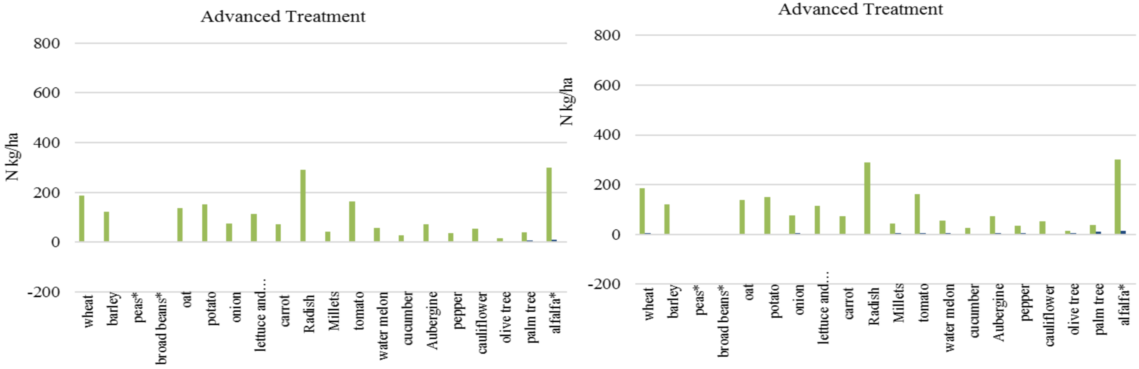
a) Nitrogen losses 50%

b) Nitrogen losses 25%



a) Nitrogen losses 50%

b) Nitrogen losses 25%



a) Nitrogen losses 50%

b) Nitrogen losses 25%

Figure 6-8 The effectiveness of conventional activated sludge, tertiary and advance treatment options under 50% and 25% of nitrogen losses

6.7 Summary

Quantifying the environmental risks from irrigation with wastewater in terms of a monetary value could be challenging due to the lack of the methodology or computer-based tools can be used to assign a value to environmental risks. One of the objectives of this research is to develop a methodology for evaluating environmental risk assessment. This objective was achieved by qualitative analysis and quantitative analysis. The formal was carried out based on the literature to identify and rank main environmental risks from a chemical in wastewater in order to select principle hazards. Due to the time constraint and availability of data, only two highly ranked hazards were used as physicochemical indicators which are salinity and excessive nitrogen. Quantitative analysis was achieved by developing a heuristic approach using Excel to assess alternative management strategies for salinity and excessive nitrogen management.

Total removing the salt from wastewater can be only achieved by advanced treatment mainly using desalination technologies such as reverse osmosis. However, in the absence of advanced treatment other salinity mitigation measures was considered which includes: regular application of effective leaching of water to transfer solutes through the soil profile and ensure the leaching of excess salt below the root zone; crop selection based on a max leaching requirement of 25% and acceptable yield loss (due to salinity) less than 10%; and finally blending with fresh water. Due to water sacristy, the latter was not applicable in our case study. The overall results have shown that the use of drip irrigation systems allows a wider range of crops to be cultivated than using sprinkler irrigation systems.

Excessive Nitrogen management in this study can be achieved by wastewater treatment, synchronizing nitrogen level to crops demand and crops selection. Synchronizing nitrogen level achieved by using a mass-balance approach. Nitrogen mass-balance includes consideration of nitrogen available to crops within the soil, nitrogen losses (e.g. nitrogen loss through ammonia volatilization, denitrification, mineralisation etc.), nitrogen content within the irrigation water, and nitrogen uptake /removed by crop. Because there is no data available from soil tests in the case study, the nitrogen level in wastewater reduced by to ratio 25% (first scenario) and 50%(second scenario) to account for nitrogen losses. To achieve the trade-off between preserving the value of nitrogen fertiliser from wastewater and mitigating the potential impacts from excessive nitrogen supply, waste stabilisation ponds in a combination of selecting crops (that can take advantage of the high level of a nutrient such as grains, leafy crops, tomato, and potato) may offer best management strategy.

Chapter 7. Costs and benefits analysis (CBA)

7.1 Introduction

While environmental and health factors drive the identification of options for water and wastewater management economics is often the crucial factor in identifying the preferred option. Costs can have a significant influence on the decision-making process, both in terms of overall costs and the balance of upfront capital costs and ongoing operational costs. For any given project to be economically viable, the net present value of all benefits should exceed the net present value of all costs.

There is a large body of literature looking at the lifecycle costs of different approaches to wastewater reuse management with a view to mitigating health risks such as (Evans and Iyer, 2012, Keraita, 2008, Seidu and Drechsel, 2010, Drechsel and Seidu, 2011, P et al., 2011). There are also a small number of studies evaluating the economics of wastewater management options for mitigating environmental risks associated with the chemical constituents in the wastewater (Molinos-Senante et al., 2011, Tziakis et al., 2009, Reymond et al., 2009, Bino et al., 2010). This chapter presents for the first time a methodology for calculating the lifecycle costs and benefits of the most effective options for managing both health and environmental risks to enable both an internal comparison and a comparison against the baseline (without project) scenario in order to identify optimum strategies for the reuse of wastewater in agricultural irrigation.

Economic analysis of cost and /benefit analysis is a well-established and accepted technique for economic evaluation; it provides efficiency metrics such as net present value, benefit/cost ratio and internal rate of return which helps to elucidate the trade-offs between the available alternatives and identify which alternative generates the best economic return (Curry and Weiss, 1993). In this study, cost benefit analysis was used to evaluate the *economic efficiency* of those risk management strategies for reusing wastewater in agriculture which had already been shown to have the best outcomes in terms of health and environment. Thus, cost-benefit analysis is the final step to identify optimum strategies for the reuse of wastewater in agricultural irrigation.

7.2 Selection of wastewater management strategies for CBA

Chapter 5 and 6 presented an evaluation of the health and environmental performance of a number of alternative management strategies for reducing risks associated with wastewater irrigation. Table 7-1 summarises the results showing the elements of the most effective strategies. The table illustrates the best combination of treatments and farm measures (mainly crop selection and irrigation method) to achieve the target health protection and minimise the risks of salinity and excessive nitrogen. These options are the ones which would ideally go forward for economic analysis. However, due to lack of data Option 1 (on-farm Three-tank system +sand Filter) was excluded. Table 7-2 thus summarises the options selected for economic analysis.

Table 7-1 Summary of the most effective risk management strategies for wastewater reuse in agriculture

Option	Treatment options	Restricted irrigation		Unrestricted irrigation	
		Crops selection	**Irrigation system**	**Crops selection**	**Irrigation system**
1	Septic tank+ On farm Septic tank+ (Three-tank system +sand Filter)	Wheat Barley Oat	Sprinkle Sprinkle Sprinkle	Wheat Barley Oat Leafy- veg tomato potato Radish	Sprinkle Sprinkle Sprinkle Drip Drip Drip Drip
2	Conventional activated sludge+ disinfection)	Wheat Barley Oat	Sprinkle Sprinkle Sprinkle	Wheat Barley Oat Leaf- veg tomato carrot potato Radish	Sprinkle Sprinkle Sprinkle Drip Drip Drip Drip Drip
3	Septic tank +WSP	Wheat Barley Oat	Sprinkle Sprinkle Sprinkle	Wheat Barley Oat Leafy- veg tomato potato Radish	Sprinkle Sprinkle Sprinkle Drip Drip Drip Drip
4	Sewerage +(WSP)	Wheat Barley Oat Millets	Sprinkle Sprinkle Sprinkle Sprinkle	Wheat Barley Oat Millets Leaf- veg tomato carrot potato Aubergine cauliflower Radish	Sprinkle Sprinkle Sprinkle Sprinkle Drip Drip Drip Drip Drip Drip Drip
5	Activated sludge+ Biological Nitrogen Removal + disinfection	Wheat Barley Millets Oat Olive tree Palm tree	Sprinkle Sprinkle Sprinkle Sprinkle Drip Drip	Wheat Barley Oat Millets Olive tree Palm tree Leafy- veg tomato carrot potato cucumber Aubergine	Sprinkle Sprinkle Sprinkle Sprinkle Drip Drip Drip Drip Drip Drip Drip Drip

Option	Treatment options	Restricted irrigation		Unrestricted irrigation	
		Crops selection	Irrigation system	Crops selection	Irrigation system
				cauliflower Radish	Drip Drip
6	Activated sludge+ Ultrafiltration+ reverse osmosis	All crops	Any system	All crops	Any system

Table 7-2: Selected option for costs and benefits analysis

Option	Wastewater treatment options	Remarket
2	WWTP (conventional activated sludge)	Sup-scenario 1: only considering wastewater from already-connected households and rehabilitate existing treatment facility
		Sup-scenario 2: Connecting household to new WWTP via construction of sewerage (operation of sewerage mostly with pumping) and effluent storage
3	Septic tank+ WSP	Requires upgrade soak away to septic tank, incentives for effluent to be delivered to WSP
4	Sewerage + WSP	Households connected to WSP via sewerage, Require construction and operation of sewerage (mostly with pumping) WSP can be centralized or decentralized,
5	WWTP (Activated sludge+ Biological Nitrogen Removal)	Household connected to WWTP via sewerage Require construction and operation of sewerage (mostly with pumping), and effluent storage
6	WWTP (Activated sludge+ Ultrafiltration UF+ reverse osmosis RO)	Household connected to WWTP via sewerage Require construction and operation of sewerage (mostly with pumping), and effluent storage

7.3 The baseline (without project) scenario

The baseline scenario is represented the best alternative option for provision of water for agriculture in the absence of the opportunity to reuse wastewater. Water for irrigation could come from only two sources in this case; desalination of sea water and the Great Man Made River (MMR). The option for increased water supply that was proposed by the government is to increase water supply from the man-made river (MMR) to include agriculture sector in addition to municipal supply. The government has recently launched a project to supply farms in the case-study area with water from man-made river phase 2 as a response to agricultural water shortage. Details of the proposed developments of the MMR are shown in Table 7-3. In the absence of a case being made for an alternative approach for irrigation, this is the option that will be implemented. It has therefore been taken as the 'baseline' or comparison case for this research.

Table 7-3 The new Irrigation water supply scheme via man-made river in Al Dafinyah area

Project consists	1. Transport pipeline and concert tank to supply Agricultural Lands Project's farms (Al Dafiniyah): 2. Internal Pipeline Network of Agricultural Lands Project's farms (Al Dafiniyah)
Total water supply m^3 /day	30,000 m^3/day
Number of farms	248

7.4 A model for calculating life cycle costs and benefits

To estimate the technical efficiency of alternative wastewater reuse strategies, an economic model using excel spreadsheet was applied to compare wastewater resus options both between themselves and against the baseline (freshwater) scenario for agricultural irrigation. The model captures and compares costs and benefits. Costs are taken to include: financial costs of construction and operation of infrastructure, costs of fertiliser and the value of health losses associated with a particular management option. Benefits are taken to include the value of crops produced and the value of the freshwater NOT used due to the implementation of the proposed option. The costs and benefits are illustrated in Figure 7-1. The model generates a number of technical efficiency indicators: Net Present Value (NPV), Benefit-Cost Ratio (BCR) and Internal rate of return (IRR)(Snell, 1997). .

The model is based on an assumed project life of 30 years, with all costs and benefits after the initial year being discounted at a rate of 3% per year. All financial values (costs and benefits) were calculated based on 2010 prices and expressed in US$ (assuming that one Libyan Dinar is worth 0.79US$(Central Bank of Libya, 2013)). The discount rate was selected as the average of annual rate of GDP growth Libya (for the period from 1990 to 2010)(WORLD BANK GROUP, 2015). Net present value is calculated as follows

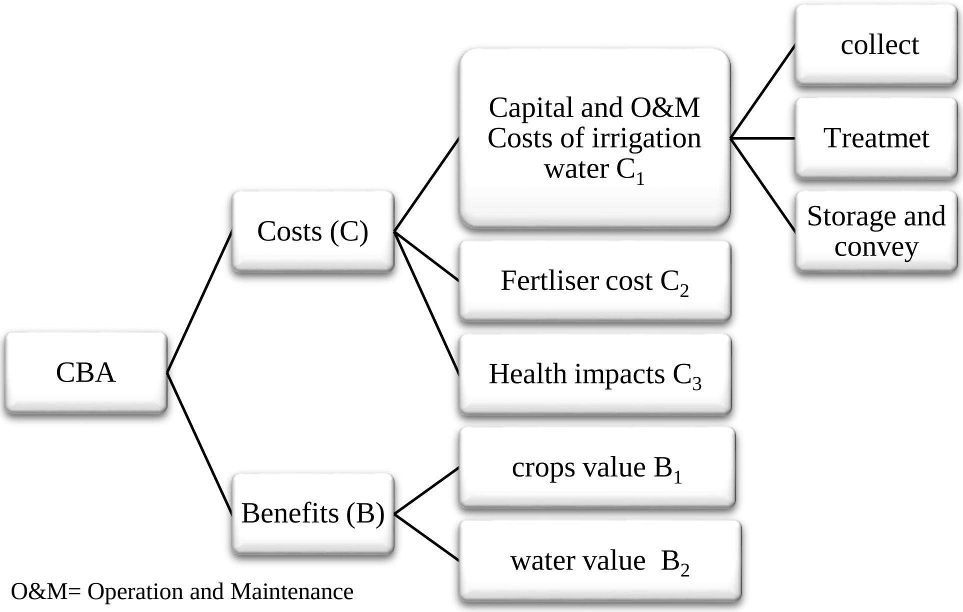
$$\text{NPV}=\sum_{t=0}^{T} \boldsymbol{B}(\mathbf{1}+\boldsymbol{r})^{-\boldsymbol{t}}-\sum_{t=0}^{T} \boldsymbol{C}(\mathbf{1}+\boldsymbol{r})^{-\boldsymbol{t}} \quad \text{Equation 7-1}$$

And benefit cost ratios are thus calculated as follows:

$$\text{BCR}=\frac{\sum_{t=0}^{T} \boldsymbol{B}(\mathbf{1}+\boldsymbol{r})^{-\boldsymbol{t}}}{\sum_{t=0}^{T} \boldsymbol{C}(\mathbf{1}+\boldsymbol{r})^{-\boldsymbol{t}}} \quad \text{Equation 7-2}$$

Where:

- T: total life cycle time (year)
- r: discount rate
- B: benefit
- C: cost
- t: year



O&M= Operation and Maintenance

Figure 7-1 Major Costs and benefits included in costs benefit analysis

7.5 Costs estimation

7.5.1 Components of costs and sources of data

Three cost components were included in the calculations: capital, operational and maintenance (O&M) costs of infrastructure; fertiliser costs; and the value of of negative health Impacts. Some of the costs estimates are based on secondary data sources, particularly information taken from government project documents. Other data were estimated or assumed based on regional and international data from journal articles and reports.

7.5.2 Capital, Operational and Maintenance Costs (C_1)

Capital costs are one-time costs and include the cost of infrastructure for the treatment, storage, and distribution of water. Operational and maintenance costs typically include energy costs, labour, chemicals and raw materials, monitoring and analyses, and equipment depreciation. Both capital, and operational and maintenance costs were estimated for the each of selected scenarios without adjustment for inflation.

7.5.2.1 Irrigation water from the man-made river (baseline scenario)

For estimating capital and O&M costs of water supplied from the man-made river, three related economic costs were included: the marginal cost of the extra water supply for irrigation from the phase 2 of MMR system; the capital costs; and O&M costs of the new project to supply target farms with water from the man-made river system.

Marginal costs of additional supply

The marginal costs of extra supply are the extra O&M costs resulting from increasing water supply from the phase 2 of MMR system, specifically to meet additional agricultural demand. Unfortunately, updated data about the volumetric costs of conveying water from the phase 2 is not available. Nevertheless, costing data from the actual economic analysis performed after completing phase one revealed that the average unit cost of water is 0.34 US$ with the cost of capital set at zero percent interest at 1991 price (Alghariani, 1997, 2003). It is generally believed that the real costs is significantly higher than this estimate primarily due to: base cost estimates are outdated and costs during the later phases of the project increased considerably since construction; costs do not take into account the depletion costs (which could be considered environmental opportunity costs) of the mined groundwater resources due to the fact that the exploited aquifers are non-renewable(Alghariani, 2003). Therefore, for this study the original volumetric cost estimate has been converted to 2010 price using a discount rate of 5% (the discount rate used in economic analysis related to man-made river project rather than the lower value applied to other elements of this analysis.) The calculation of PV (present value at 2010) is shown below. Table 7-4 show the estimate of marginal costs to convey 10.95 million cubic meters of water annually for irrigation supply.

$$\mathrm{PV} = \mathrm{C}(1 + 0.05)^{19} \qquad \text{Equation 7-3}$$

Capital costs of new irrigation works

The second cost component is the capital investment required for the new Irrigation water supply scheme to deliver water from phase 2 to the farm gate. These are estimated based on the contract value of the project in the year 2010 as reported from(the man- made river authority, 2010).

Operational costs of irrigation

The final related costs are the O&M costs of running the new scheme. These were estimated based on a similar project of utilizing water for the man-made river in the city of Benghazi-Libya in 1993(Consulting office for economic studies, 1993). From this project, it has been found that the average annual O&M costs are around 2% of capital investment in the project. Therefore, the annual O&M costs of the new scheme were estimated as 2% of the capital costs.

Summary costs

Table 7-4 provides the total capital costs and estimated O&M costs of the new scheme

Table 7-4 Cost of transport water via MMR at 2010 price

Cost per cubic meter at 1991 price US$	Present value at 2010	
	Cost of cubic meter US$	Cost of 10.95 million m^3 /year US$
0.34	0.86	9,417,000

Source: Author estimate

Table 7-5 Summary of cost estimates of the new irrigation water supply scheme

Description	Capital costs US$	O&M costs US$/year
Transport pipeline and concert tank for break pressure	8,501,750.708	170,035.0142
Internal distribution Network to farm gate	70,749,794.74	1,414,995.90
TOTAL	79,251,545.45	1,585,030.909

Source: Author estimate

7.5.2.2 Capital and O&M costs estimates of selected wastewater reuse strategies

The selected wastewater management options for costs and benefits analysis are:

- **Option 2(i): connect household to WWTP (Conventional activated sludge AS) using existing connected households and rehabilitation of existing WWTP**

In this scenario, the only effluent from existing wastewater treatment plant will be reused for irrigation (which represent only 25% of wastewater generated in the city). Therefore, costs of collecting and treatment included in this case were the rehabilitation costs and O&M costs of wastewater treatment plan, O&M costs of exciting sewerage network, treatment plan, and costs of effluent storage and convey to farms.

- **Option 2(ii): connect household to WWTP (conventional activated sludge AS) new treatment plant and sewerage**

In this scenario, it is assumed that around 70% of the city's population could be connected to a new wastewater treatment facility using a new sewer network. Therefore, the costs element included was capital and O&M costs of new facilities, capital and O&M costs of the new sewerage system, the cost of effluent storage and convey to farms.

- **Option 3: connect septic tanks to WSP:**

This option requires incentives for wastewater from household to be delivered to a new WSP. It assumes the provision of onsite facilities (that includes septic tank and holding tank) and well-regulated and properly financed collection services. The costs included were the costs of upgrading soakaway tanks to onsite facilities, costs of delivering wastewater to WSP, costs of the de-sludging septic tank, costs of construction and operating WSP, and finally costs of conveying effluent to farms.

- **Option 4: connect household to WSP via sewerage:**

This option assuming around 70% of the population will be connected to waste stabilisation ponds instead of conventional treatment facilities via sewerage. Costs estimates include the cost of construction and operating WSP, costs of sewerage networks and costs of effluent convey to farms.

- **Option 5: connect households to a new WWTP (conventional Activated sludge (AS+ Biological Nitrogen Removal BNR)**

Wastewater treatment facilities considered in this option will include tertiary treatment to remove nitrogen from wastewater. The costs included were costs of treatment facilities, sewage networks, and effluent storage and conveyance (including costs of operation of the network).

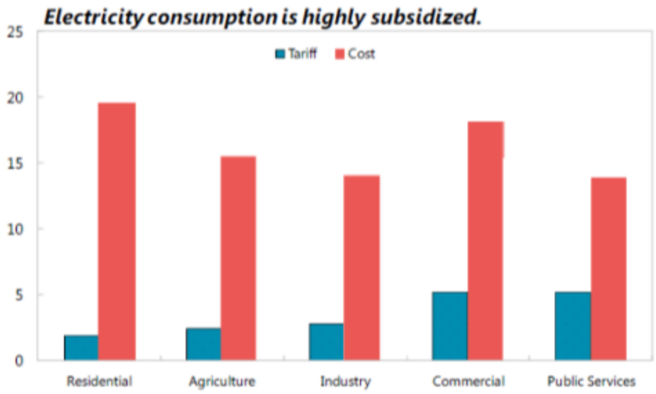
- **Option 6 connect households to a new WWTP (Activated sludge+ Ultrafiltration UF+ reverse osmosis RO)**

This considered using Ultrafiltration UF and reverse osmosis RO for advanced treatment after conventional activated sludges treatment. The cost elements for this option are costs of treatment facilities, sewage networks, and effluent storage and conveyance.

The cost of Wastewater collecting systems

Operational and maintenance costs of existing sewerage network:

The main costs considered are the cost of pumping and regular maintenance. As there is a lack of data regards to capital maintenance of existing sewerage network, the network was assumed to be in good condition. Annual maintenance costs for the existing network are reported in(General Water and Wastewater Company 2012). Generally, electricity is provided at prices that are considerably below the world market; electricity costs are routinely subsidised by the government from the annual budget. It has therefore been estimated that overall recovery of electricity costs is very low ranging from 7.7% to 37.5% in the residential sector and public services respectively. Figure 7-2 shows actual electricity tariffs and estimated actual costs of production and delivery for 2010 for different sectors(International Monetary Fund, 2013). The real cost of electricity for agriculture demands is around 0.15US $ per kilowatt/ hour which is significantly higher that the tariffs that farmers pay (less than 0.05US$ /kilowatt hour) for their supply.



Sources: General Electric of Libya, Economic Studies Department.
[1]Data for 2010. In 2012 the residential tariffs was 1.5 U.S. cents.

Figure 7-2. Libya: Electricity Tariffs and Costs1, 2010 (U.S. cents per kilowatt hour)

To achieve realistic economic efficiency estimates, the real cost of electricity provided in Figure 7-2 was taken for estimating the energy consumption costs. These were applied to estimates of O&M costs and are reported in Table 7-6 .

Table 7-6: Operational and maintenance costs of sewerage network

Description	**O&M Costs US$**
Annual maintenance	760,000.00
Pumping costs (0.12US$/Kwh)	1,809,640.8
Salary	410,400.00
Total	2,980,040.8
Pumping energy Kwh/yr	15,080,340.00

Source: (General Water and Wastewater Company 2012)'updated to reflect actual energy costs

Construction of new sewerage network:

There is lack of data related to the actual costs of construction of a new sewer network; most of the available literature focuses on network optimisation models and strategies. Only a small number of publications have developed cost functions for sewerage networks and they are developed for site-specific conditions (Abraham et al., 1998, Fenner, 2000, Tafuri and Selvakumar, 2002, Yeh et al., 2008, Ugarelli et al., 2009, Dogot et al., 2010, Hunter Water Corporation, 2012, Rehan et al., 2014, Hernández-Sancho et al., 2015). Even if one of these functions could be adapted, it was difficult to implement due to lack of data from the case study. To overcome this problem, these costs was estimated based on the cost of installation of new sewerage in one district of the city assuming the city is homogenous, and the cost increases proportionally with the population as it is shown in Table 7-7. Data for the original cost estimate was reported in (Housing & Infrastructure Board, 2013).These costs are estimates only and there is uncertainty around them as the cost of sewerage is driven by site-specific conditions.

Table 7-7 Costs estimates of installation of new sewerage networks

	Actual network	New network
Design population	50,000	500,000
Capital costs	37,161,372.49	371,161,372.49
O&M	743,227.45	7,423,227.45

Source: Author estimate

Costs of upgrading and operating of on-site facilities:

These costs including the cost of installation of septic tanks followed by holding tanks and the costs of emptying and transporting wastewater to the treatment site.

The capital cost of installation of the septic tank followed by holding tank was estimated based on the typical cost of installing septic tanks system in housing projects in the case study (based on information provided by key informants/ householders in the city).

For emptying and transporting wastewater to the treatment site, the most common practice is the use of a vacuum truck The approach to estimating operational costs for management of onsite systems was adapted from (Evans et al.)(forthcoming). Estimates of capital costs, typical capital maintenance, replacement periods, the costs of operational wear and tear, and unit costs for labour were elicited based on the local market. The costs of fuel were assumed based on report of International Monetary Fund 2013. Information on the time needed to empty a typical storage tank and de-sludge septic tank, typical house size (people per unit), the time needed to transfer wastewater to the treatment site and the time needed to transfer sludge to disposal were assumed based on the researcher's own knowledge, interviews with householders and an analysis of Google Earth images to assess travel distances. It is worth to mention that most of these data were planned to be collected through interviews and observation during the field work. Table 7-8 provides the size and the costs of installation of on-site facilities, unit costs of labour and fuel and the costs of emptying and transport wastewater to treatment site are summarized in Table 7-9 and Table 7-10 respectively.

Table 7-8 The size and the costs of installation of on-site facilities

Elements	Unit	Value
House size (persons)	Persons	6 persons
Septic tank	Liter	5,400
holding tank	Liter	24,00
Capital of installation	US$	3,000

Source: Author estimate

Table 7-9 Unit costs of labour and fuel

Element	Unit	value
Wages		
Skilled Labor	US$/month	380
Working hours		
Working hours (2 shift)	Hours	16(8)
Working days per week	Day	6
Fuel costs	US$/Liter	0.16

Source: Author estimate

Table 7-10 The costs of emptying and transport wastewater to treatment site

Element	Unite	value
Loading/Emptying Time	Mints	60
Average Distance between households and potential treatment sites	km	10
Travel speed	Km/hour	30
Loading/Emptying Time	Mints	60
Size of truck	Liter	15,000
Capital costs		
Capital cost of truck	US$	45,000
Capital maintenance/ replacement period	years	15
Capital maintenance cost	% capital costs	100
Operational wear and tear	% capital costs	15
OPERATIONAL COSTS		
Wage		
Nr of skilled operators		2(1)
Labour costs	US$/year	9,120(4560)
Other operational costs		
Fuel consumption	Liter/km	0.2
Cost of fuel	US$/km	0.032

Source: Author estimate

The total of 84,000 households was estimated based on the reported average household size of 6, and a population of 500,000 inhabits. Typical holding tanks will need to be emptied approximately twice per month and de-sludging of septic tanks will be required once per year. For the whole population, that results in the need for 2,184,000.00 emptying events each year, and a total of 30.3 million m^3 of wastewater to be transported annually. Emptying and transporting wastewater to treatment site will require 560 vacuum trucks and 1,120.00 labours.

Table 7-11 summarizes the total costs require to collect and transport wastewater from on-site facilities to the treatment site.

Table 7-11 Summary of cost estimates to collect and transport wastewater from on-site facilities to treatment site

Elements	Capital cost US$	O&M US$	Capital maintenance US$
On-site facilities	504,000,000.00		
Vacuum truck	25,200,000.00	3,780,000.00	25,200,000.00
Labour		5,107,200.00	
Fuel		1,308,160.00	
Total	529,200,000.00	10,195,360.00	25,200,000.00

Source: Author estimate

Treatment costs

Rehabilitation of existing treatment plant:

The existing treatment plant is reported to work well. However, it has a number of operational problems including; damage in chlorination unit resulting in periodic shut downs; deterioration of the condition of some elector-mechanical equipment; and difficulty of operating the grit and greases removal units due to illegal connection of some commercial activities to sewerage networks (General Water and Wastewater Company 2012). In addition to that, the plant laboratory suffers from a lack of equipment and supplies for operation which results in an inability to carry out some tests such as heavy metal and microbiological tests. In 2010 the plant was assigned for rehabilitation with a total cost of **3,588,203.96** US$. For O&M costs**,** based on data from an annual report about O& M costs in 2010 (wastewater treatment plan-Misurata), Table 7-12 illustrate the O&M costs of existing wastewater treatment facilities.

Table 7-12 The O&M costs of existing wastewater treatment facilities

Description	US$/Year
Energy costs 0.12 US$/Kw/hr	295,488
Chemical	27,360
Salary	273,600
regular maintenance	31,920
Total	628,368.01

Source: (GENERAL MANEGAR 2013. wastewater treatment plan, Misurata) updated to reflect actual energy costs

A new conventional activated sludge treatment plant:

The new treatment plan will be designed for 70% of 2040 population (715,000). Therefore the plant capacity will be around 120,000 m^3 /day for design population of 500,000. The capital and operational costs of treatment facilities were extracted from the literature. The capital cost of conventional activated sludge fund in the relatively new publication in literature range from 100 to 150$ per capita and operational and maintenance costs vary between 4 to 8 $ per capital (Rao et al., 2015, Libhaber and Jaramillo, 2012). In this study capital and O&M costs presented in Table 7-13 was estimated based on the highest unit cost presented in relatively new publication in the literature to represent worst case scenario taken into account the population growth.

Table 7-13 Capital and O&M costs of conventional activated sludge treatment plant

Capital costs	**US$**
Per capital	150
Design population 500,000	75,000,000
O&M costs of the first year of operation	**US$/year**
Per capital	8
Population 260,000	2,100,000

Waste stabilisation ponds:

The WSP will be designed for 70% of 2040 population. Therefore the design population would be of 500,000. . In general, the cost of waste stabilisation ponds will depend on their size which, in turn, is based on the designed removal efficiency. Thus the outline design of waste stabilisation ponds is based on the selected removal efficiency (from chapter 5 and 6). Ideally primary data would have been used to calculate the cost of construction and O&M per unit area of typical ponds. However, due to time and data constraints, the costing data used in this study (Table 7-14) was extracted from the literature and based on the highest reported unit costs for developing countries. Costs are therefore calculated conservatively – and represent a worst-case scenario.

Table 7-14 Capital and O&M costs of Waste stabilisation ponds

Capital costs $	**US$**
Per capital	50.00
Design population 500,000	25,000,000.00
O&M costs of the first year of operation	**US$**
Per capital	0.4
Population 260,000	104,000.00

Tertiary treatment (Biological Nitrogen Removal):

According to (Gratziou and Chrisochoidou (2011), Sperling and de Lemos Chernicharo (2005)) the costs of biological nitrogen removal processes ranges from 5% to 20% of the cost of conventional activated sludge depending on the type of technology and the required removal efficiency. In this research, we assumed that the additional costs required for remove nitrogen from wastewater are 10% of the costs of conventional activated sludge. Table 7-15shows the additional costs required for biological nitrogen removal.

Table 7-15 Cost estimates of Biological Nitrogen Removal

Elements	Cost US$
Capital costs	7,500,000.00
Additional O&M costs of the first year of operation	210,000.00

Source: Author estimate

Advanced treatment (UF+RO):

The capital cost of advanced treatment (Table 7-16) was estimated based on the costs of advanced treatment plant with a capacity of 3,000 m^3/day (Wastewater Treatment Plant in Libyan Iron and Steel Complex 2010). Generally, larger plants have higher capital costs; however, the capital cost for a larger plant is unlikely to increase proportionally with the plant capacity due to economies of scale. This requires knowledge of the relationship between capital costs and plant capacity. Thus, in this research, the empirical relationship (Equation 7-4) between capital costs and plant capacity reported by (Shahalam et al., 2012, Gebrezgabher et al., 2015) is used to scale up the capital costs:

$$C_x = C_y \left(\frac{Q_x}{Q_y}\right)^{\mu} \qquad \text{Equation 7-4}$$

where Cx is the cost of capital for a large plant with a specific capacity; Cy is the cost of capital for a small plant with its actual capacity (which in this case is 3000 m^3/d); Qx is the capacity of a large plant; Qy is the capacity of the existing plants (i.e., 120,000 m^3/d); μ is the parameter representing economies of scale. Because the extent of the economies of scale (μ) in the larger plant is not known. To overcome this obstacle, the parameter μ was assigned values of 0.85 which represents reasonable levels of economies of scale(Shahalam et al., 2012).

Although all cost components to a certain degree are affected by plant capacity, one of the main components affected by plant capacity is the capital cost. For simplicity, it is assumed that there are no economies of scale in O&M costs. This assumption is more conservative as O& M costs will be even lower in the case of applying economies of scale. The unit O&M costs are presented Table 7-16, these costs were estimated based on the literature (Alhumoud et al., 2010, Haruvy et al., 2008, Jamaly et al., 2014, Knops et al., 2007, Halpern et al., 2005, Pearce, 2008).

Table 7-16 The cost of advanced wastewater treatment (UF - RO)

Plan capacity	Capital cost US$
Plant capacity 3000 m^3 /day	6,800,000.00
Plant capacity 120 000 m^3 /day	156,408,339.50

Source: Author estimate

Table 7-17 O&M Cost estimates of advanced wastewater treatment (UF - RO)

Elements	US$/$m^3$
Energy costs (0.12 US$/KWH)	0.19
RO membrane replacement and RO membrane cleaning	0.02
Other O&M costs	0.07
Total O&M	0.28

Source: Author estimate

The cost of wastewater storage and conveyance to farms

These costs were estimated based on a proposed project in Misurata to transfer wastewater from a WWTP to the south of the city for the purpose of irrigation of an area of forestry (Housing & Infrastructure Board Libya- middle region 2012). Table 7-18 shows the capital costs estimates. The annual operation and maintenance costs includes energy costs for pumping, salaries and annual maintenance of pumping stations.

Table 7-18 Costs estimates of wastewater storage and convey to farms

Description	Capital costs	O&M
Cost effluent storage reservoir	2,806,345.16	-
Effluent convey and pumping	$47,427,593.43	$993,564.40

Source:(Engineering Consulting Office for Utilities, 2012).

With respect to wastewater distribution to the farm gate, there is an existing irrigation water distribution network which has previously been used to distribute irrigation water. It is assumed that this network can be used to distribute wastewater effluent to farm gate, it consists of storage tanks and canals to the farm gate; water in these channels flows under gravity. Currently, the network is out of work due to groundwater deterioration. In general, the network is in good shape, it only requires minor maintenance. Because of the lack of data, the costs of these minor repairs were not included in the analysis. This is assumed to be an insignificant source of error since the impact of these costs is small compared to other more significant costs.

7.5.2.3 O&M cost of irrigation systems:

Wastewater irrigation can has effects on the irrigation system. It can contain suspended solids, High organic matter content, biological agents, and high concentrations of Ca and Mg. all these contents can cause of partial or full clogging of micro irrigation systems such as drippers and sprinklers and subsequently reduce the efficiency of irrigation system. Therefore, irrigation systems needs more regular maintenance when wastewater used for irrigation. However because of lack of data with regards to the additional costs that may be required for the O& M of irrigation systems as results of using wastewater. These costs was not included. However, as an economic costs at national level these costs might not be significant compare to other capital and O&M costs.

7.5.2.4 Summary of Capital, Operational and Maintenance Cost estimates (C1)

Summaries of the capital costs and operational and maintenance costs for the baseline scenario and the selected management options for wastewater reuse in irrigation are presented in Table 7-19.

Table 7-19 Table capital, and operational and maintenance costs of selected wastewater reuse options

Options	Related economic costs	Capital costs million US$	Annual cost of O&M million US$
MMR	Transport fossil groundwater to farm gate via MMR	79.25	1.59
Option 2- sub-scenario i	Collecting system	-	2.98
	Treatment	3.59	0.63
	Convey and storage	50.23	0.99
Option2- sub- scenario ii	Collecting system	371.16	7.42
	Treatment	78.59	2.73
	Convey and storage	50.23	1.55
Option 3	Collecting system	529.2	10.19
	Treatment	20.00	0.11
	Convey and storage	47.43	0.99
Option 4	Collecting system	371.16	7.42
	Treatment	25.00	0.11
	Convey and storage	47.43	1.55
Option5	Collecting system	371.16	7.42
	Treatment	90.00	2.52
	Convey and storage	50.23	1.55
Option 6	Collecting system	371.16	7.42
	Treatment	231.41	9.5
	Convey and storage	50.23	1.55

Source: Author estimate

7.5.3 Fertiliser costs estimate C_2

Fertiliser costs to farm gate were estimated using the following formulas:

Fertiliser costs = $\sum Chemical\ fertliser\ demands\ (\ ton) \times\ \ fertiliser\ price\ (\frac{US\$}{ton})$. Equation 7-5

Chemical Fertiliser demandes (ton) = $\sum[(\boldsymbol{crop\ nutrient\ requirment}\ \left(\frac{kg}{ha}\right) - \boldsymbol{nutrients\ \ from\ wastewater}\left(\frac{kg}{ha}\right) - \boldsymbol{nutrient\ available\ from\ soil}\left(\frac{kg}{ha}\right)) \times \boldsymbol{area}(\boldsymbol{ha}) \times \mathbf{0.001}]$. Equation 7-6

Crop nutrient requirement= crop nutrient removal (kg/ton)× crop yields (ton/ha) Equation 7-7

As mentioned in chapter 6, crop nutrient uptake values and crop yield data were mostly taken from IFA recommendations(Wichmann, 1992) and presented in (Table 6-8, chapter 6). These values are based on typical nutrient concentrations and yields for good growing conditions.

The selection of chemical fertilisers was based on available chemical fertilisers in the local market. The most common fertiliser and their price are presented in Table 7-20.

Table 7-20 Common fertiliser used by farmers in the case study

Fertilizer	**US$/ton**
P Fertilizer	
Diammonium phosphate	$1,216.00
K fertilizer	
Potassium sulphate	$836.00
N fertilizer	
Urea	$760.00

Source: Author estimate (Based on local market)

These values are therefore applied in each case to estimate the total cost of fertilisers in the given cropping scenario, where some nutrient requirements will be met from NPK in wastewater in some cases.

7.5.4 Costs estimates of Health impacts C_3

Based on the researcher knowledge of the farming activities supported by consulting key informants, the principal crops cultivated in the study farms are grains and fodder followed by raw vegetables. Therefore, for the costs and benefits analysis, the potential scenario with respect to agriculture activities would be unrestricted irrigation practices. For the calculation of the economic value of health impacts, the total DALY loss from alternative scenarios was considered and associated with an economic loss (salary loss) using the following formula:

- Economic value= Total DALY loss x Annual Wage Equation 7-8
- Total DALY loss= population×∑(Disease Risk pppy× DALY loss per case of disease) Equation 7-9

As mentioned in chapter 5 it was estimated it was assumed that 30% of the population would be at health risk from consuming raw vegetables irrigated with wastewater. The resultant health risk in each case is associated with the relative quality of the wastewater, from a microbiological point of view, after the relevant treatment option has been applied.

To convert DALY loss to an economic, value the annual wage was estimated based on average salary per capita in Libya was reported 500 LYD/month, corresponding to 6000 LYD/year or 4560 USD/year.

7.6 Benefits estimation

7.6.1 Crops value B_1

The crop value was estimated using the below formula, where crops price was taken from the minimum market price in case study Table 7-21.

Crops value= $\sum crop\ yeid\ \left(\frac{ton}{ha}\right) \times area(ha)\ \times crop\ price\ \left(\frac{US\$}{ton}\right)$ Equation 7-10

Identifying, the optimum crops pattern for achieving the greater economic efficiency, requires optimisation analysis that considers, climate condition, water use efficiency, fertiliser requirement soil, local and national market, and labour and machine requirement. Because of time constraint and difficulty to access data from the case, such analysis was beyond the scope of this study. For simplicity, therefore a simplified cropping pattern was assumed in all cases based on the preferred crops of grains and fodder with a small area dedicated to raw vegetable. Table 7-22 provides the most likely crops pattern in the target farms. The total area that can be cultivated is a function of the volume of water supply and the total irrigation water requirement (Equation 7-11).

$total\ area\ (ha) = \frac{\sum \boldsymbol{TR_C}}{Q}$ Equation 7-11

Where:

- TR_C the total irrigation water requirement for each crop (m^3/ha/year) (see chapter 6, Table 6-5)
- Q (m^3/year) the volume of water supply.

Table 7-21 Crops yield and price.

Crops	Target Marketable Yields (ton/ha)	Market price US$/ton
Fodder:		
alfalfa	15/year	**760**
oat	5 (grain) 9.8 TDM	**646**
Grains:		
wheat	6.7 grain 13.7 TDM	**380/ton(hey)** **760/ton(grain)**
Barley (winter)	6.8 grain 11 TDM	**380/ton(hey)** **570/ton(grain)**
Vegetable:		
lettuce and Green-Leaf Crops	**30**	**760**
Radish	**20**	**760**
carrot	**25**	**1140**
tomato	**27**	**760**
potato	**30**	**1900**

Table 7-22 Crops pattern and land use

CROPS	**Portion of area %**
Fall winter season	
Grain	50
Fodder	30
potato	10
Raw Vegetable	10
Spring –summer season	
Tomato	20
Raw vegetable	10
Land use	130

7.6.2 Fresh Water value B_2

Fossil water in Libya is a finite resource. It has intrinsic value to the economy of Libya due to its potential as a long run source of critical drinking water and as buffer against future external economic shocks. Such a shock might limit the economic value of alternative water sources (i.e. desalination). Therefore, the fossil water is deemed to have an economic value at the national level independent of its financial costs or benefit to individual farmer. This national economic value is therefore considered in the analysis.

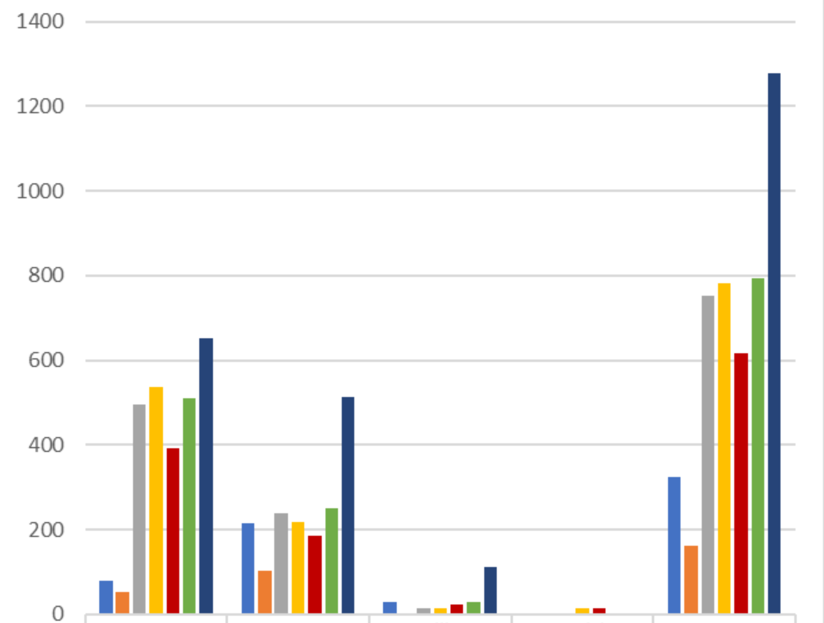
The value of fresh water is the value or opportunity cost saved due to water not required from other sources i.e. water being saved or exchanged with other users. In this research, fresh water value was considered as the avoided marginal O&M costs of transport water via man-made river for agricultural supply.

7.7 Summary Results

7.7.1 Economic costs and benefits

For each option, a cost function was constructed which comprised initial capital costs incurred in initial years plus an annual operation and maintenance budget incurred in each year of an assumed 30-year lifecycle. These costs were then summed and discounted to give a total project present value of costs; similarly, all annual benefits were summed and discounted to give a total project present value of benefits. The present value of costs (including capital costs, O&M costs, fertiliser costs and costs of health impact) and the present value of benefits (including the crops yield and fresh water value) of alternative wastewater reuse options, are given Figure 7-3 and Figure 7-4 respectively in Million US$ over 30 years of the life cycle. It is clear that from Figure 7-3 advanced treatment has the highest costs compare to other alternative strategies of wastewater reuse. The figure also shows that option 2 sup-scenario 1 (Rehabilitate current treatment plant) have the lowest costs of all alternative strategies of wastewater reuse. Comparing the capital costs and O&M costs of option 3 (connect septic tanks to WSP) and option 4(connect household to WSP via sewerage). It can be seen, installation of sewage network has about (20%) lower costs than upgrading on-site facilities; this could be contributed to high frequency of emptying events as results of high level of water consumption per capita. The results also show that apart from option 2 sup-scenario 1 all the wastewater reuse strategies have higher total cost compare to water from MMR. By looking at O&M costs and fertiliser costs, the lower costs of MMR and option 2 sup-scenario 1 could be because of the sunk costs related to capital costs of both options. The results also indicated that the value of the negative of health impacts are not significant compared to the capital and O&M costs.

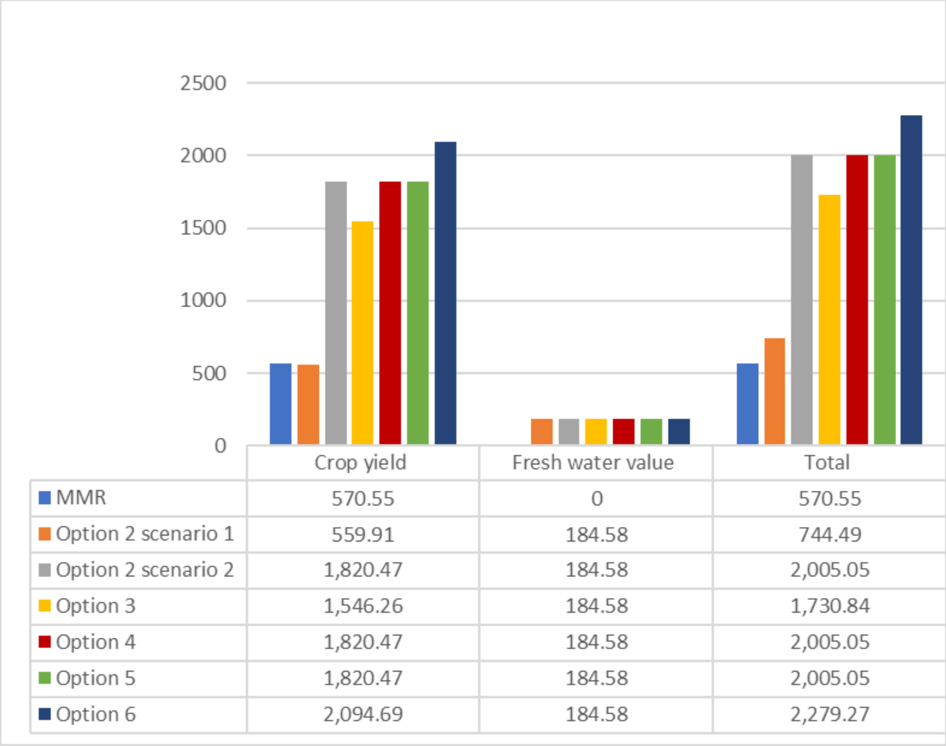
With regards to total net present benefits of alternative wastewater reuse. The Figure 7-4 shows that all wastewater reuse options have higher benefits that MMR. The figure also indicates that, although the advanced wastewater treatment has the highest costs, it provides the highest crop yields. This is due to the significant decrease of water salinity and subsequently, reduced demand due to leaching requirement and the impact of salinity on crops yield. By comparing the benefits of option (3) and option (4) option 4 has a crop yield 15% higher than option 3, this can be contributed to the lower volume of wastewater collected from on-site facilities per year is slightly lower (30. 21 million m^3/ year) compared to sewer network (30.66 million m^3/year). Also, the results show that the option 2 sub-scenario 1 have the lowest crops yield compare to all alternative including MMR.



	Capital costs	O&M costs	Fertiliser costs	Health impact costs	Total
■ MMR	79.25	215.64	28.85	0	323.74
■ Option 2 scenario 1	53.82	101.79	3.97	3.54	163.12
■ Option 2 scenario 2	496.39	238.45	13.98	3.54	752.36
■ Option 3	536.2	217.38	13.82	14.95	782.35
■ Option 4	391.16	186.64	23.16	14.96	615.92
■ Option 5	511.39	249.5	29.69	3.54	794.12
■ Option 6	652.8	514.42	110.45	0.029	1277.699

Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

Figure 7-3 Costs estimate Million US$



	Crop yield	Fresh water value	Total
■ MMR	570.55	0	570.55
■ Option 2 scenario 1	559.91	184.58	744.49
■ Option 2 scenario 2	1,820.47	184.58	2,005.05
■ Option 3	1,546.26	184.58	1,730.84
■ Option 4	1,820.47	184.58	2,005.05
■ Option 5	1,820.47	184.58	2,005.05
■ Option 6	2,094.69	184.58	2,279.27

Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

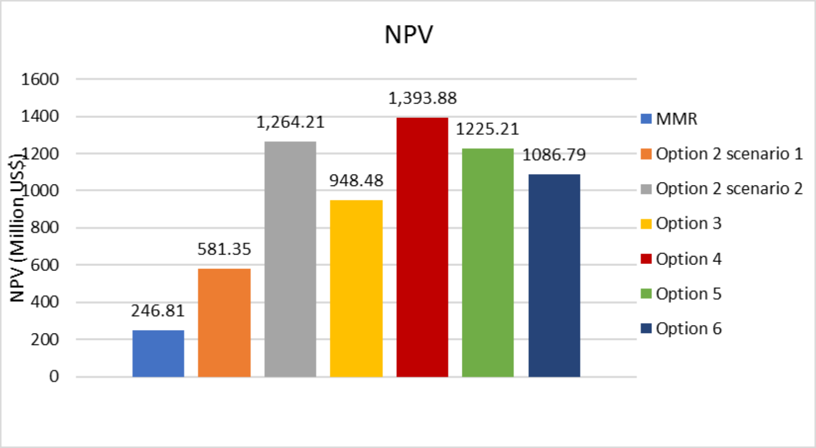
Figure 7-4 Benefit estimates Million US$

7.7.2 Costs- benefits indicators

The total present value of costs and benefits presented in Figure 7-3 and Figure 7-4 are used to calculate the net present value NPV, B/C ratio, and IRR are for each option and the results presented in Figure 7-5, Figure 7-6, and Figure 7-7 respectively.

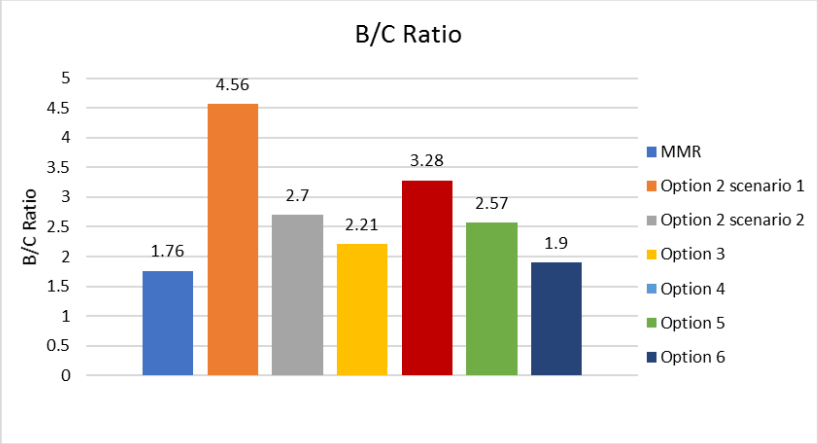
From Figure 7-5 it can be seen that all wastewater reuse options have higher NPV than MMR with option 4 have the highest value of (1,393.88 million US$) followed by option 2 sub-scenario 2 (Connect households to a new treatment plant via sewerage network), while option 2 sup-scenario1 have the lowest NPV (581.35 million US$) compare to other wastewater reuse options.

The results of B/C ratio and IRR shown in Figure 7-7 and Figure 7-6, indicated that despite having the lower NPV option2 sup-scenario 1 have the highest B/C ratio with a retune of more than 4 times its cost and IRR of 60%, as it has been mentioned earlier this could be due to the suck costs in capital investment compare to other alternatives. The results also show that all wastewater reuse options have higher B/C ratio than MMR with the return of their costs were two times and higher. In contrast, IRR results shows that all of the wastewater reuse options (except option 2 – sup-scenario 1and option 4) have lower IRR (< 20%) compare to MMR (20.92%).



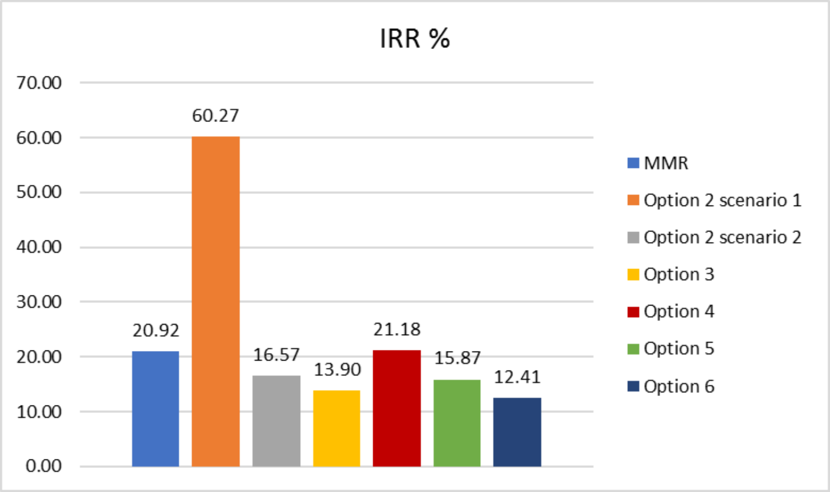
Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

Figure 7-5 Net present values of alternative options



Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

Figure 7-6 Benefits -Costs Ratio



Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

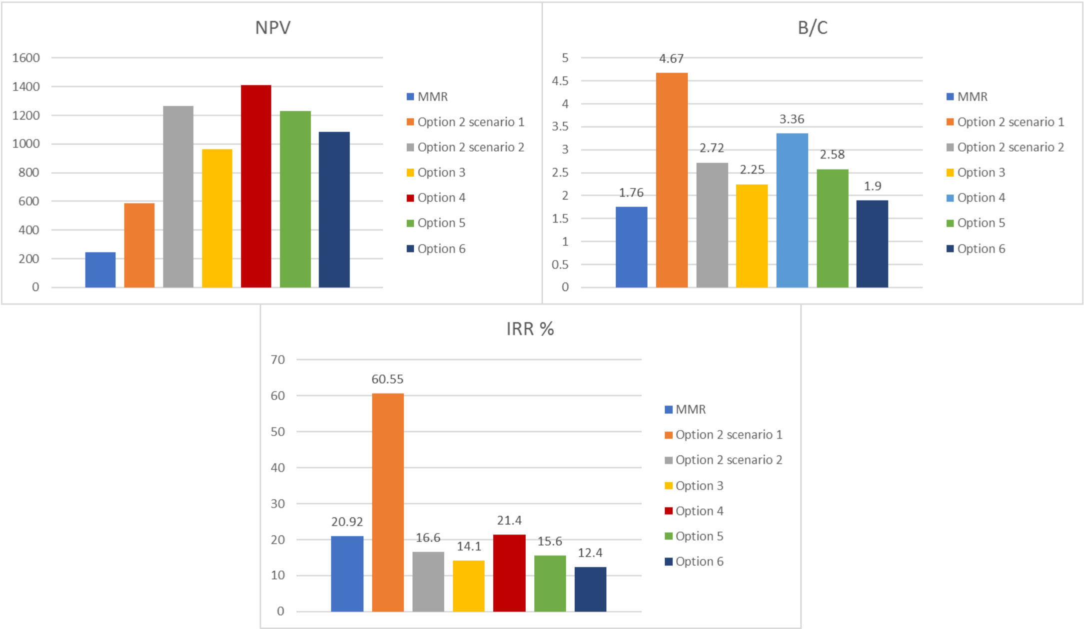
Figure 7-7 Internal rate of return

The results presented above show that comparing with MMR all alternative wastewater reuse options are economically acceptable with B/C ratio higher than 2 and IRR between (12 to 21 %). The results also show that the most effective options for wastewater reuse in agriculture for this case study is to rehabilitate current treatment plant facilities and the second-best alternative is to connect household to WSP via sewerages.

7.7.3 Financial analysis

Most of costs and benefits included in this study were financial costs and benefits, only costs of health impacts are economic costs. Many economic costs and benefits such as (economic prices of fertiliser and grain crops as results of import substitutes, the environmental benefit of avoiding groundwater abstraction, social costs and shadow price of wastewater value, economic costs of sludge disposal and management) were not included in this research due to the lack of data.

The options can also be evaluated on a purely financial basis by excluding the value of the negative health impact and the results are presented in Figure 7-8. The results clearly show that the value of negative health impacts does not have any significant effect and the economic analysis and financial analysis provide almost the same NPV and B/C ratio for all alternatives.



Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

Figure 7-8 Financial analysis

7.7.4 Sensitivity analysis

Sensitivity analysis was conducted to assess the robustness of the economic- model results under different input values of main variables. Because of some degree of uncertainty related to parameters and data used to quantify costs and benefits, a number of sensitivity tests have been carried out in a simplified way to identify which economic variable are critical in determining the indicators values. the sensitivity tests include:

For the cost side:

- The impact of decreasing costs of marginal O&M costs of transport cubic meter via man-made river -10%
- the impact of increasing capital, operating and maintenance costs of wastewater reuse option +10%
- the impact of decreasing capital, operating and maintenance costs of wastewater reuse option -10%
- the impact of increasing fertiliser costs +10%
- the impact of decreasing fertiliser costs -10%

For the benefit side:

- the impact of excluding the value of fresh water
- the impact of increase crops value +10%
- the impact of decrease crops value -10%

The analysis was also made to ascertain the effects of variations in the discount rate on the costs- benefits indicators by increasing the discount rate from 3 % to 8%, 10%, and 12%.

Figure 7-9, Figure 7-10, Figure 7-11 and Figure 7-12 present the results of sensitivity tests at discount rate of 3%, 8%, 10, and 12 % respectively. The results indicated excluding fresh water value has a high impact on B/C ratio and NPV especially at discount rate 12%. The results also show that B/C ratio and NPV are mostly sensitive to capital and O&M costs and crops values especially at discount rate higher than 10% (particularly option 6, option3 and option 5) while they are not largely sensitive to fertiliser costs and costs of health impacts. Excluding option 3, option5 and option 6, all other wastewater reuse options have higher B/C and NPV than MMR in all sensitivity tests. The results also show that option 6 might not be economically acceptable as it quite sensitive to changes in almost all variable especially at discount rate 10 % or above. Finally, from all sensitivity tests, it is a clear that option 2 senario1 followed by option 4 are the most effective wastewater reuse options for this case study with the highest B/C ratio and NPV ratio.

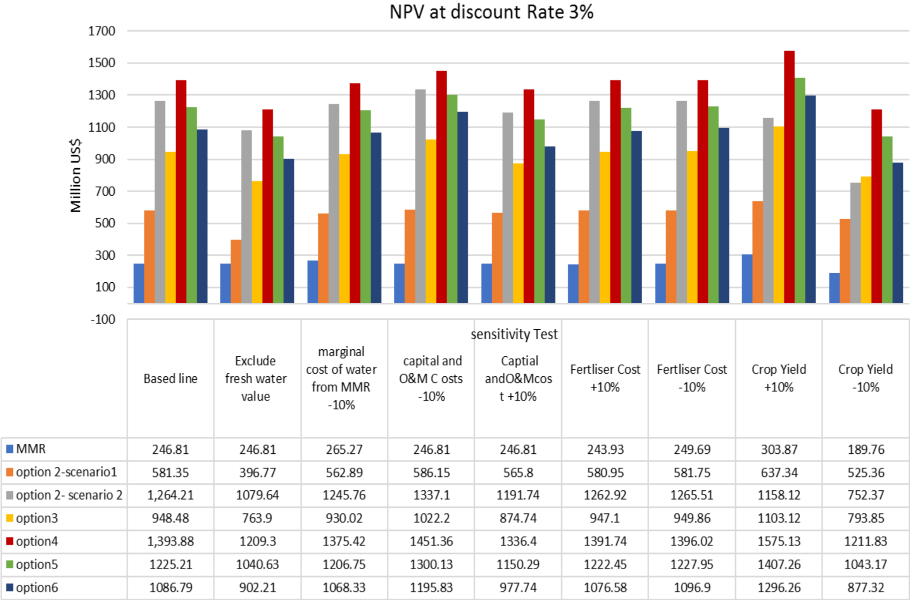
7.8 Summary

In this chapter costs benefits analysis was used to evaluate the economic efficiency of the most effective risk management strategies for reusing wastewater in agriculture to decide which of these management strategies are economically justified (in which the expected benefits are greater than the costs) and which once generate greater economic return compared to utilising water from man-made river project (without project).

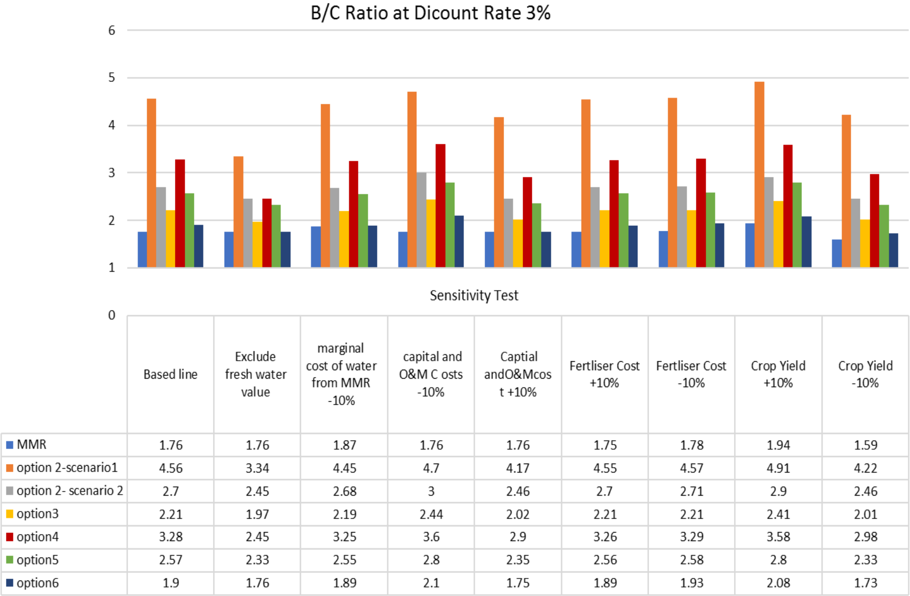
For CBA, the costs included were capital costs, O&M costs, fertiliser costs and costs of health impact) and the benefits included were the crop yield and fresh water value). Most of these costs and benefits were financial costs and benefits, only costs of health impacts are economic costs. Many economic costs and benefits (such as economic prices of fertiliser and grain crops as results of import substitutes, the environmental benefit of avoiding local groundwater abstraction, social costs, shadow price of wastewater value, and the economic costs of sludge disposal and management) were not included in this study because of data limitations.

The results of this costs and benefits analysis reveal that comparing with MMR all alternative wastewater reuse options (excluding advanced treatment option) are economically acceptable with B/C ratio higher than 2 and IRR between (12% to 21 %). However, these results are sensitive to forecasts of capital and O&M costs, of crops yield, and discount rate. Also, the results reveal that in arid and semi-arid zones such as Libya in addition to agriculture benefits, water value is an important drive for wastewater reuse in agriculture.

For this case study, the results conclude that the most effective options for wastewater reuse in agriculture are to rehabilitate current treatment plan facilities with the highest B/C ratio or to connect household to WSP via sewerage with the highest NPV. The results also show that advanced treatment may not be economically acceptable as it quite sensitive to changes in almost all variable especially at discount rate higher than 10%.



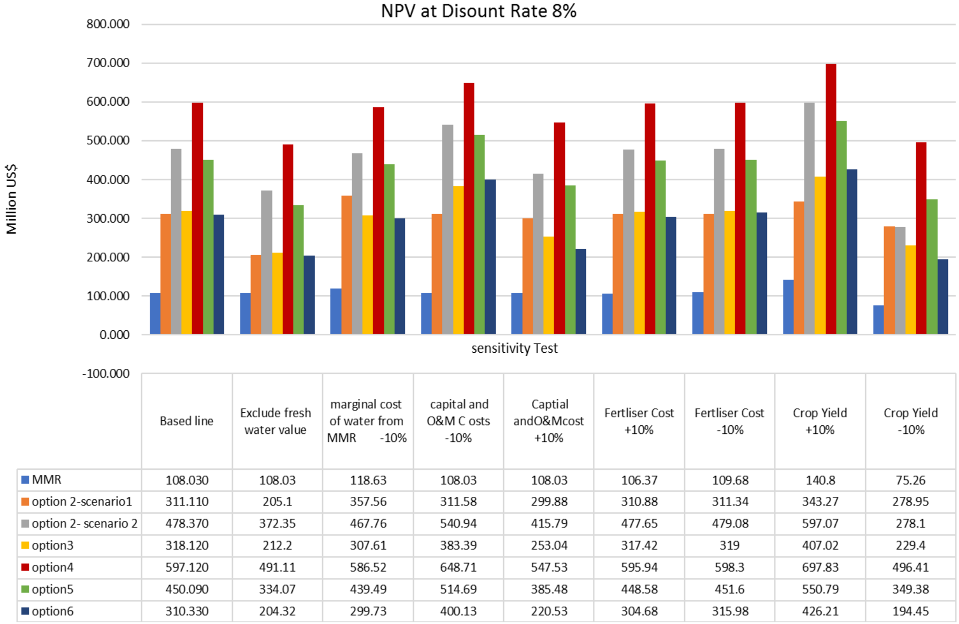
	Based line	Exclude fresh water value	marginal cost of water from MMR -10%	capital and O&M C osts -10%	Captial andO&Mcos t +10%	Fertliser Cost +10%	Fertliser Cost -10%	Crop Yield +10%	Crop Yield -10%
MMR	246.81	246.81	265.27	246.81	246.81	243.93	249.69	303.87	189.76
option 2-scenario1	581.35	396.77	562.89	586.15	565.8	580.95	581.75	637.34	525.36
option 2- scenario 2	1,264.21	1079.64	1245.76	1337.1	1191.74	1262.92	1265.51	1158.12	752.37
option3	948.48	763.9	930.02	1022.2	874.74	947.1	949.86	1103.12	793.85
option4	1,393.88	1209.3	1375.42	1451.36	1336.4	1391.74	1396.02	1575.13	1211.83
option5	1225.21	1040.63	1206.75	1300.13	1150.29	1222.45	1227.95	1407.26	1043.17
option6	1086.79	902.21	1068.33	1195.83	977.74	1076.58	1096.9	1296.26	877.32



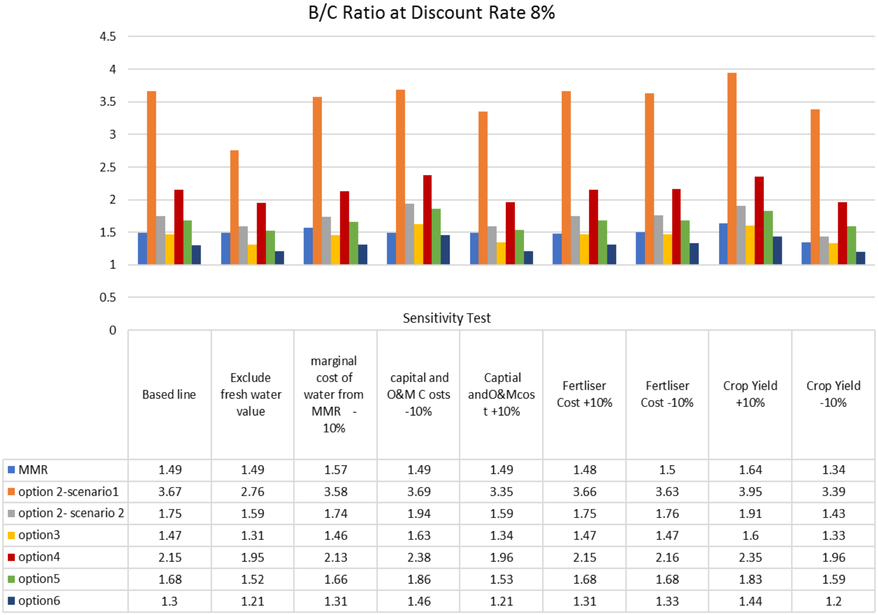
	Based line	Exclude fresh water value	marginal cost of water from MMR -10%	capital and O&M C osts -10%	Captial andO&Mcos t +10%	Fertliser Cost +10%	Fertliser Cost -10%	Crop Yield +10%	Crop Yield -10%
MMR	1.76	1.76	1.87	1.76	1.76	1.75	1.78	1.94	1.59
option 2-scenario1	4.56	3.34	4.45	4.7	4.17	4.55	4.57	4.91	4.22
option 2- scenario 2	2.7	2.45	2.68	3	2.46	2.7	2.71	2.9	2.46
option3	2.21	1.97	2.19	2.44	2.02	2.21	2.21	2.41	2.01
option4	3.28	2.45	3.25	3.6	2.9	3.26	3.29	3.58	2.98
option5	2.57	2.33	2.55	2.8	2.35	2.56	2.58	2.8	2.33
option6	1.9	1.76	1.89	2.1	1.75	1.89	1.93	2.08	1.73

Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

Figure 7-9 Sensitivity tests at discount rate 3%



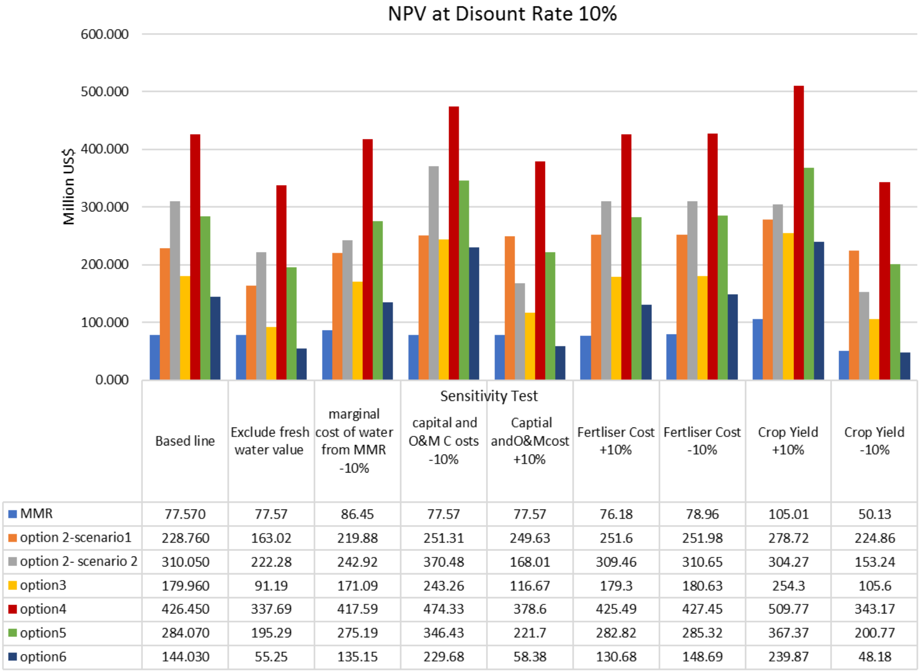
	Based line	Exclude fresh water value	marginal cost of water from MMR -10%	capital and O&M C osts -10%	Captial andO&Mcost +10%	Fertliser Cost +10%	Fertliser Cost -10%	Crop Yield +10%	Crop Yield -10%
MMR	108.030	108.03	118.63	108.03	108.03	106.37	109.68	140.8	75.26
option 2-scenario1	311.110	205.1	357.56	311.58	299.88	310.88	311.34	343.27	278.95
option 2- scenario 2	478.370	372.35	467.76	540.94	415.79	477.65	479.08	597.07	278.1
option3	318.120	212.2	307.61	383.39	253.04	317.42	319	407.02	229.4
option4	597.120	491.11	586.52	648.71	547.53	595.94	598.3	697.83	496.41
option5	450.090	334.07	439.49	514.69	385.48	448.58	451.6	550.79	349.38
option6	310.330	204.32	299.73	400.13	220.53	304.68	315.98	426.21	194.45



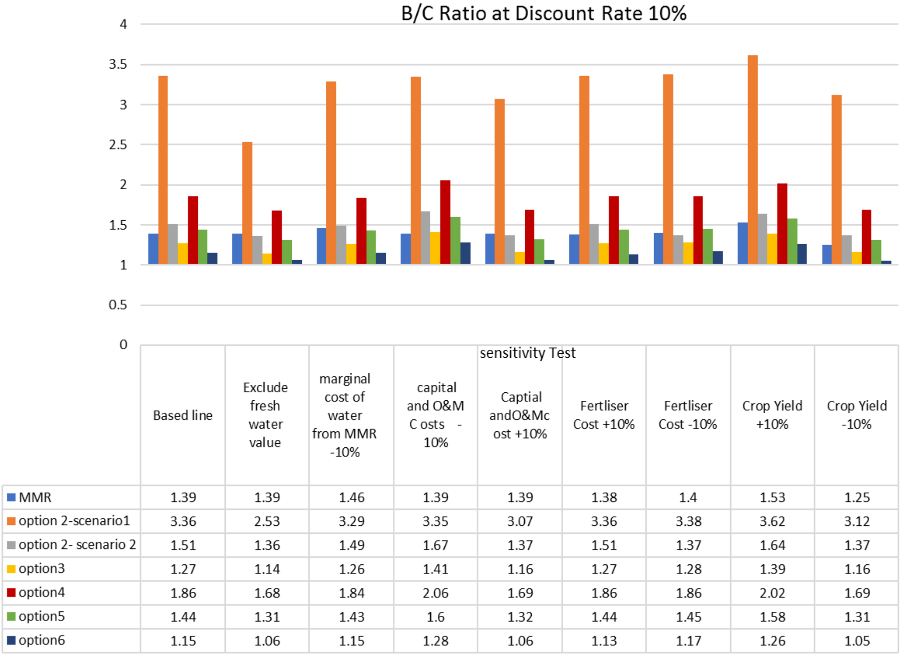
	Based line	Exclude fresh water value	marginal cost of water from MMR - 10%	capital and O&M C osts -10%	Captial andO&Mcos t +10%	Fertliser Cost +10%	Fertliser Cost -10%	Crop Yield +10%	Crop Yield -10%
MMR	1.49	1.49	1.57	1.49	1.49	1.48	1.5	1.64	1.34
option 2-scenario1	3.67	2.76	3.58	3.69	3.35	3.66	3.63	3.95	3.39
option 2- scenario 2	1.75	1.59	1.74	1.94	1.59	1.75	1.76	1.91	1.43
option3	1.47	1.31	1.46	1.63	1.34	1.47	1.47	1.6	1.33
option4	2.15	1.95	2.13	2.38	1.96	2.15	2.16	2.35	1.96
option5	1.68	1.52	1.66	1.86	1.53	1.68	1.68	1.83	1.59
option6	1.3	1.21	1.31	1.46	1.21	1.31	1.33	1.44	1.2

Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

Figure 7-10 Sensitivity tests at discount rate 8%



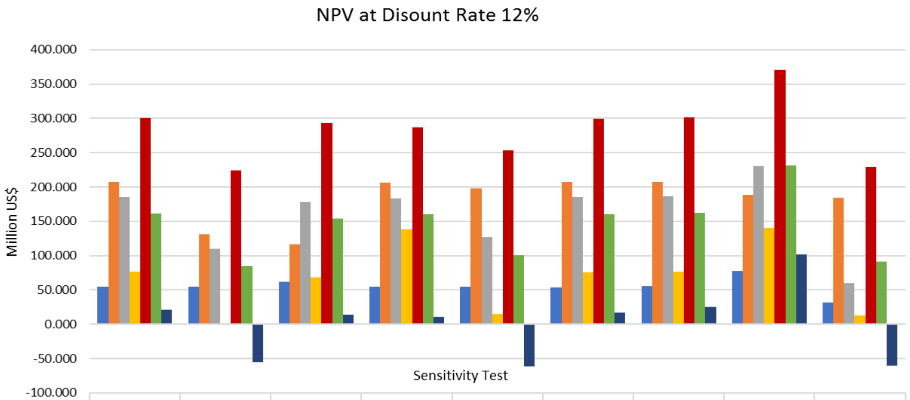
	Based line	Exclude fresh water value	marginal cost of water from MMR -10%	capital and O&M C osts -10%	Captial andO&Mcost +10%	Fertliser Cost +10%	Fertliser Cost -10%	Crop Yield +10%	Crop Yield -10%
🟦 MMR	77.570	77.57	86.45	77.57	77.57	76.18	78.96	105.01	50.13
🟧 option 2-scenario1	228.760	163.02	219.88	251.31	249.63	251.6	251.98	278.72	224.86
■ option 2- scenario 2	310.050	222.28	242.92	370.48	168.01	309.46	310.65	304.27	153.24
🟨 option3	179.960	91.19	171.09	243.26	116.67	179.3	180.63	254.3	105.6
🟥 option4	426.450	337.69	417.59	474.33	378.6	425.49	427.45	509.77	343.17
🟩 option5	284.070	195.29	275.19	346.43	221.7	282.82	285.32	367.37	200.77
🟦 option6	144.030	55.25	135.15	229.68	58.38	130.68	148.69	239.87	48.18



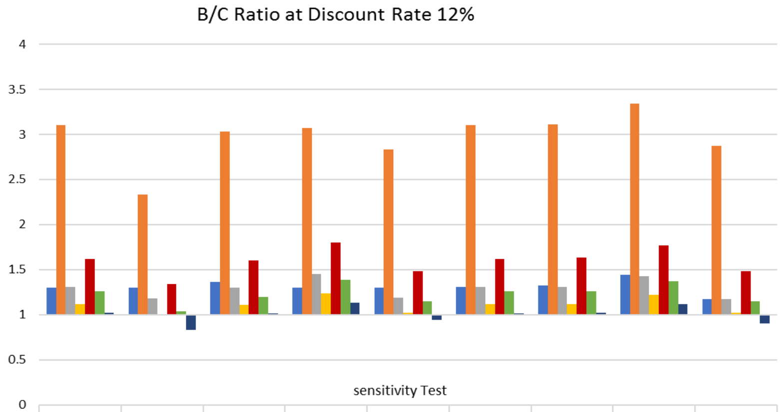
	Based line	Exclude fresh water value	marginal cost of water from MMR -10%	capital and O&M C osts - 10%	Captial andO&Mc ost +10%	Fertliser Cost +10%	Fertliser Cost -10%	Crop Yield +10%	Crop Yield -10%
🟦 MMR	1.39	1.39	1.46	1.39	1.39	1.38	1.4	1.53	1.25
🟧 option 2-scenario1	3.36	2.53	3.29	3.35	3.07	3.36	3.38	3.62	3.12
■ option 2- scenario 2	1.51	1.36	1.49	1.67	1.37	1.51	1.37	1.64	1.37
🟨 option3	1.27	1.14	1.26	1.41	1.16	1.27	1.28	1.39	1.16
🟥 option4	1.86	1.68	1.84	2.06	1.69	1.86	1.86	2.02	1.69
🟩 option5	1.44	1.31	1.43	1.6	1.32	1.44	1.45	1.58	1.31
🟦 option6	1.15	1.06	1.15	1.28	1.06	1.13	1.17	1.26	1.05

Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

Figure 7-11 Sensitivity tests at discount rate 10%



	Based line	Exclude fresh water value	marginal cost of water from MMR -10%	capital and O&M C osts -10%	Captial andO&Mcost +10%	Fertliser Cost +10%	Fertliser Cost -10%	Crop Yield +10%	Crop Yield -10%
■ MMR	54.750	54.75	62.33	54.75	54.75	53.56	55.94	78.2	31.3
■ option 2-scenario1	207.54	131.49	116.54	206.15	197.78	207.18	207.51	188.67	184.33
■ option 2- scenario 2	185.500	109.64	177.92	183.1	126.68	185	186	230.35	59.59
■ option3	76.370	0.511	68.78	138.26	14.48	75.8	76.93	139.91	12.82
■ option4	300.190	224.33	292.6	286.71	253.62	299.36	301.02	370.61	229.75
■ option5	161.220	85.36	153.63	160.17	100.52	160.16	162.25	231.62	90.8
■ option6	20.960	-54.89	13.37	11.22	-61.6	17.02	24.9	101.98	-60.06



	Based line	Exclude fresh water value	marginal cost of water from MMR -10%	capital and O&M C osts -10%	Captial andO&Mcost +10%	Fertliser Cost +10%	Fertliser Cost -10%	Crop Yield +10%	Crop Yield -10%
■ MMR	1.3	1.3	1.36	1.3	1.3	1.31	1.32	1.44	1.17
■ option 2-scenario1	3.1	2.33	3.03	3.07	2.83	3.1	3.11	3.34	2.87
■ option 2- scenario 2	1.31	1.18	1.3	1.45	1.19	1.31	1.31	1.43	1.17
■ option3	1.12	1	1.11	1.24	1.02	1.12	1.12	1.22	1.02
■ option4	1.62	1.34	1.6	1.8	1.48	1.62	1.63	1.77	1.48
■ option5	1.26	1.04	1.2	1.39	1.15	1.26	1.26	1.37	1.15
■ option6	1.02	0.83	1.01	1.13	0.94	1.01	1.02	1.12	0.9

Option 2 scenario 1	Excising sewerage and treatment plan (AS)
Option 2 scenario 2	New sewerage and treatment plan (AS)
Option 3	connect septic tanks to WSP
Option 4	connect household to WSP via sewerage
Option 5	connect household to (a new WWTP (AS+ BNR)
Option 6	connect household to (a new WWTP (AS+ UF+RO)

Figure 7-12 Sensitivity tests at discount rate 12%

Chapter 8. Review of the methodology and Conclusion

8.1 Introduction

The existing literature on wastewater reuse shows a strong bias toward technical publications. On one hand, there is a well-established literature looking at the health risk associated with wastewater irrigation and the lifecycle cost of alternative wastewater reuse management for health risk mitigation; on the other hand, There is a lack of studies providing any mechanism or implemented models to quantitatively assess the management of the environmental risks resulting from reusing wastewater in agriculture. In particular very few studies have attempted to evaluate the economics of wastewater management options for mitigating environmental risks associated with the chemical constituents in the wastewater.

This research one of a very small number of studies which attempt to bring together health and environmental risk assessment and management with economic analysis. Thus this study presents:

1. the first attempt to systematically apply quantitative microbial risk assessment (QMRA) to assess different strategies for wastewater reuse in agriculture in Libya;
2. A novel approach for systematically assessing different strategies for environmental risk management which is relevant to arid areas in developing countries and first applied to Libya to validated ; and finally
3. A method to assess the lifecycle costs and benefits of alternative strategies for wastewater reuse in agriculture to optimise the trade-offs between risks to public health and the environment and the preservation of the substantial benefits.

8.2 Review and discussion of the methodology

The aim of this research was to develop a novel integrated approach that combines health risk assessment, environmental risk assessment, and economic analysis to enhance the sustainable management of wastewater reuse in agriculture. This study provides a tool for decision makers which can be used to compare various wastewater management options and to determine the most suitable scale at which treatment alternatives and interventions are possible, feasible and cost effective.

The tool that has been developed is a spreadsheet-based model that combines health risk assessment, environmental risk assessment and costs -benefits analysis:

1. Health risk assessment was conducted using a well-known computer programme MC-QMRA (Quantitative Microbial Risk Assessment and Monte Carlo computer program). The results from the MC-QMRA were incorporated into the model as input data and used to estimate health impacts in terms of DALYs.

   MC-QMRA has been widely used for ascertaining the health risks associated with wastewater reuse in both developing and developed countries. This study is one of the first in which QMRA has been applied in a case study from Libya to assess the potential health risks from wastewater reuse in agriculture.

   Although there are various combinations of wastewater treatment options and post-treatment measures that could be implemented for pathogen risk reduction, due to a lack of data, the study considers only three risk management measures. These are: wastewater treatment methods, wastewater application methods and crop selection under two scenarios of human exposure. However, other measures such as post-harvest options could be incorporated relatively easily when the required data are available.

   The results of the health risk assessment confirm that health protection from wastewater irrigation does not necessarily require conventional centralised treatment facilities. The results also show that using other options such as low-cost wastewater treatment including an on-farm three tank system followed by a sand filter, and waste stabilisation ponds are sufficient for reducing the pathogen risks to acceptable levels especially when combined with post-treatment measures such as crop selection and drip irrigation.

2. Environmental risk assessment was conducted using a heuristic approach using Excel to develop the model to assess and compare alternative wastewater management strategies for mitigating the environmental risks from wastewater irrigation

   Since the case study was an arid zone where surface water is limited, findings based on a qualitative risk assessment suggested that excessive salt and excessive nitrogen were the most significant hazards arising from wastewater irrigation. Although, the research only focussed on salinity effect from excessive salt and did not include any sodicity effects. The latter can be easily incorporated into the model when the data is available by estimating the quantity of soil amendment needed to achieve an acceptable EC-SAR relationship.

   Like the health risk assessment, a combination of treatment options, wastewater application methods, and crop selection methods were evaluated for salinity and excessive nitrogen management. For salinity management, the model estimates the leaching requirement based on the salt tolerance threshold of the crop and the water salinity level for given crops with a maximum allowable leaching fraction (≤ 0.25).

Leaching requirement in this research was estimated using the traditional approach which is based on steady-state conditions (Rhoades, 1974, Ayers and Westcot, 1985, Hoffman, 1985). This approach is commonly used in the literature for the design and management of irrigation system and wastewater land application (Hillel, 2000, Simmons et al., 2010, Minhas, 1996, Duan et al., 2011b, Hanson et al., 1999).

The results show that most of the conventional and non-conventional wastewater treatment methods considered are not effective at removing excessive salt from wastewater. Removal of total dissolved solid from wastewater generally requires desalination. Therefore, in the absence of wastewater desalination, the results shows that for effective salinity management, in this particular case study and due to a high level of salinity, using drip irrigation is essential to allow a wider range of crops to be cultivated.

Managing the potential impacts associated with excessive nitrogen was achieved by wastewater treatment, synchronizing the applied nitrogen level to crop demand and crop selection. Synchronizing the level of nitrogen applied was achieved by a simplified mass-balance approach using "approximate N budgets to evaluate „what if‟ scenarios. Nitrogen mass-balance includes consideration of the existing nitrogen available to the crops within the soil, nitrogen losses (e.g. nitrogen loss through ammonia volatilization, denitrification, mineralisation etc.), nitrogen content of the irrigation water, and nitrogen uptake /removal by the crop.

For achieving the trade-off between the reduction of the potential impacts from excessive nitrogen and preservation of the fertiliser value in the wastewater, the results suggest that waste stabilisation ponds together with careful selection of crops such as grains, leafy crops, tomato, and potato (which can take advantage of the high level of a nutrient) may be the best option for managing excessive nitrogen

3. The costs -benefits analysis model was developed for calculating and comparing the costs (including: capital costs, O&M costs, fertiliser costs and costs of health impact) and the benefits (including crop yield and fresh water value) from the alternative wastewater reuse strategies considered in this study to decide which of these management strategies are economically justified compared to a baseline scenario (which in this case study transport fossil groundwater via the man-made river). Most of these costs and benefits were financial costs and benefits, only the costs of health impacts are economic costs.

8.3 The overall results

The results of the costs and benefits analysis revealed that in comparison to the MMR, most of the alternative wastewater reuse options are economically acceptable with B/C ratios higher than 2 and IRR between 12% and 21 %. However, these results are sensitive to forecasts of capital and O&M costs, crops yields, and the discount rate. The results also show that upgrading the on-site facility and providing well-regulated and properly financed collection services have higher costs than a sewerage system and lower the NPV and B/C ratio are low due to low benefits comparing to the capital and O&M costs of the system. The high cost of this system may be impacted by the high level of water consumption which resulted in a high frequency of emptying events. However, to reduce the costs of managing onsite facilities, a solid-free sewerage system might provide a better option than using a vacuum tanker. This option could not be included in the analysis due to a lack of data. The results of costs and benefits analysis concluded that for greater economic return, the best option for wastewater reuse in agriculture (compared to other considered alternatives) is to connect households to waste stabilisation ponds via a sewerage system

8.4 Applicability of the proposed tool to other case studies

In general, the proposed methodology could be applied to other similar case studies to identify effective management options for wastewater reuse in agriculture. The spreadsheet model could also be applied to other case studies in arid and semi-arid regions with similar agro-ecological features. However, the following considerations need to be taken into account:

- The model was developed based on a specific case study and therefore, adjustments may be required to identify the alternative management options for wastewater reuse in agriculture, such as treatment options, on farm-based measures and agricultural activities and crop pattern
- The environmental risk assessment mainly focused on excessive salt and excessive nitrogen as the most significant hazard in arid and semi-arid regions where surface water is scarce. This may not be the case in other areas.
- Calculating the potential costs and benefits are subject to data availability for the case study under analysis, therefore adjustment may be required to include other costs and benefits which are not estimated in this case study.

8.5 Achievement of the research outcomes

1. The main achievement of this research is the development of a decision- making tool which can be used to evaluate alternative management strategies for wastewater reuse in agriculture, the model has the following advantages:
    - It combines health and environmental risk assessment and economic analysis.
    - It is easy to use and does not require advanced skills.

  - It has a high degree of flexibility for application to other case studies.
  - The input data and model structures can be easily modified to incorporate other risk management options and engineering interventions.
  - The outcomes are illustrated in tables and graphs which make it is easy to interpret
  - The model is structured as a supply chain system where output data from one stage works as input data for next stage (e.g. risk assessment results are used for cost-benefit analysis
2. This study has also has shown that in the context of Libya, wastewater reuse appears to be a more reliable and cheaper water resource for agricultural supply than the transport of fossil groundwater via the man-made river. Integration of wastewater reuse for agriculture in national water resource management strategies could potentially result in a reduction in groundwater withdrawals, and consequently, enhance groundwater conservation and the preservation of high-quality fresh water currently used in agriculture for other prior demands including environmental demands

8.6 Limitations of the research

1. Data availability issues: most of the data used in this study was based on typical data from the literature or extrapolation of data with different degrees of uncertainty. The proposed research plan was based on obtaining a primary data from the case study and should this primary data be difficult to collect, then secondary data from the case study or from literature would be used as an alternative. However, due to fact that the proposed fieldwork in Libya could not be carried out as a consequence of the instability and unrest in Libya at the time of this study, it was difficult to access data sources from the case study area. Thus, most of the data used was secondary and proxy data (based on secondary data sources, particularly information taken from government project documents or assumed based on regional and international data from journal articles and reports). Nevertheless, the secondary data from the literature has been selected very carefully with high relevance to the case study. It is believed that the outcome of this research will not change significantly if the fieldwork has been lunch and primary data has been used.

2. The costs and benefits analysis was primarily based on financial analysis rather than economic analysis and many economic costs and benefits were not included in this study due to data and time constraints. This includes the O&M costs of irrigation system, the economic prices of fertiliser and grain crops as a result of import of substitutes, the environmental benefit of avoiding groundwater abstraction, social costs and the shadow price of wastewater value and also the economic costs of sludge disposal and management.

3. The research initially attempted to evaluate the feasibility of the different combinations of treatment and farm based interventions. However, due to the lack of data, most of the assessed management strategies were based on the installation of treatment facilities (mostly centralised). Other options could have been evaluated if data was available such as a combination of low cost of wastewater collection systems, on-farm treatment, and post-treatment measures.
4. Despite the advantages of the developed model, it has also some drawbacks including:
    - Developing the model requires a substantial amount of specific data from different specialist fields and a knowledge of some other computer-based programmes such as QMRA and the CROPWAT software.
    - The numeric values that are generated are only indicative and dependent on the quality of the data input. Therefore, this tool can only be used for comparing and prioritizing agricultural activities and wastewater management strategies and it cannot be used for detailed risk assessment, costing purposes and/or design purposes.
    - In the case of availability of new data input, the model requires revalidation and may require some modification for adapting to the new data.

8.7 Conclusion

Meeting the continuous increase in water demands often comes with high environmental costs including the depletion of natural water sources such as rivers and groundwater quality deterioration due to seawater intrusion.. In many countries, especially where water resources are limited, the available water supply has been stretched to its limits and an imbalance between water supply and water demand has reached critical levels. Globally, agriculture is by far the largest consumer of water, accounting for approximately 70 percent of all freshwater withdrawal and up to 90-100 percent in developing countries. Libya, like many arid and semi-arid regions, is facing serious water scarcity combined with malpractice of available water resources management which has increased the pressure on this precious resource. Nearly 80% of the country’s water supply is utilised in agricultural activities while the economic contribution to the national income from this sector has been insignificant in last few decades. In the absence of legal or financial incentives, the agricultural sector is likely to be a highly inefficient user of the resource contributing to more water shortage problems. Wastewater reuse is an alternative water source to address water scarcity and its availability and its nutrient properties make it the most reliable water supply for agricultural irrigation practice. However, inappropriate management of wastewater reuse can pose substantial risks to public health and the surrounding environment because of its microbial and toxic components. Sustainable wastewater reuse management is quite complex and requires consideration of several technical and non-technical aspects including health aspects, environmental and natural resources, technical feasibility, and the social-cultural and political aspects.

Given the increasing interest in the economics of wastewater reuse, there is still a lack of any robust systematic analytical approach for comparing various options to optimise the trade-offs between public health and the environment protection and preservation of the substantial environmental and social benefits. This research attempts to address this issue by developing a new evaluation tool for the decision maker to optimise wastewater management options. The new tool is a spreadsheet-based model that combines the assessment of both health and environmental effects and economic analysis. The model was developed based on a case study in Misurata in northern Libya to assess various management options of wastewater reuse and to decide which of these management strategies are effective and economically justified compared to a baseline (transport of fossil groundwater via the man-made river for irrigation purposes). Although the model was based on the case study from Libya, it can be applied to other case studies in arid and semi-arid regions with similar agro-ecological features. In the Libyan case study, the overall results concluded that for effective risk management and greater economic return, the optimum option for wastewater reuse in agriculture (compared to other considered alternatives) is to connect households to waste stabilisation ponds via a sewerage system.

8.8 Recommendations and suggestions for further work

1. Further work is required to improve the environmental risk assessment model to include other environmental risks and risk management options for other environmental hazards such as sodicity, heavy metals, and emerging contaminants.
2. Further work is required to apply QMRA to evaluate the current wastewater management and sanitation in the case study using real field work data.
3. Further work can be done to use real field data to validate and consolidate the outcome of this research.
4. For a more comprehensive economic analysis, other economic costs and benefits (such as economic values of import substitutes, the environmental benefit of avoiding groundwater abstract, social costs and shadow price of wastewater value, economic costs of sludge disposal and management) should be included in costs and benefits analysis. Also, there is a need to look at the economic analysis from a public policy perspective and the financial impact on key stakeholders (such as farmer).
5. To conserve the economic sustainability, there is an urgent need to properly address the increase in water scarcity and re-evaluate the long-term water resources management strategies. In the context of integrated water resource management, wastewater reuse

appears to be an alternative reliable water resource especially in arid and semi-arid countries such as Libya where water supply is heavily reliant on groundwater. Integrating wastewater reuse for agriculture in national water resource management strategies will result in a significant reduction in groundwater withdrawals, and consequently, preserve the limited conventional water resources for more economically and socially valuable purposes such as drinking water in urban areas, and industrial and commercial activities with high-income production.

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Annex 1

Quantitative Microbial Risk Assessment and Monte Carlo simulation

The third edition of WHO(2006) guidelines for safe use of wastewater, excreta and grey water in agriculture have adopted QMRA and 10000 iteration Monte Carlo simulations for risk analysis. The dose-respond equation for the reference pathogens are:

For Cryptosporidium

$P_I(d) = 1 - e^{(-rd)}$ (Exponential dose-response model)

For rotavirus and Campylobacter:

$P_I(d) = 1 - [1 + \left({}^{d}/_{N_{50}}\right)\left(2^{1/\alpha} - 1\right)]^{-\alpha}$ (Beta-Poisson dose–response model)

Annual risk infection:

$P_{I(A)}(d) = 1 - [1 - P_I\,(d)]^n$

Where:

PI(d) is the risk of infection in an individual exposed to a single pathogen dose d

PI(A)(d) is the annual risk of infection in an individual from n exposures per year to the single pathogen dose d

N50 is the median infective dose and

α and are pathogen “infectivity constants:

For rotavirus N50 = 6.17 and α = 0.253; for Campylobacter N50 = 896 and α = 0.145; and for

Cryptosporidium r = 0.0042 (Haas et al., 1999)

A1.1 Tolerable risk of infection

the guidelines set “design” risk of rotavirus infection is taken as 10^{-3} pppy. This value is extremely safe as it lower at least by three magnitude that the actual diarrhoeal incidence in the world

Table 1: Diarrheal disease (DD) incidence pppy in 2000 by region and age

Region	DD incidence All ages	DD incidence 0-4	DD incidence 5-80+
Industrialized countries	0.2	0.2-1.7	0.1-0.2
Developing countries	0.8-1.3	2.4-5.2	0.4-0.6
Global average	0.7	3.7	0.4

(Mathers et al., 2002)

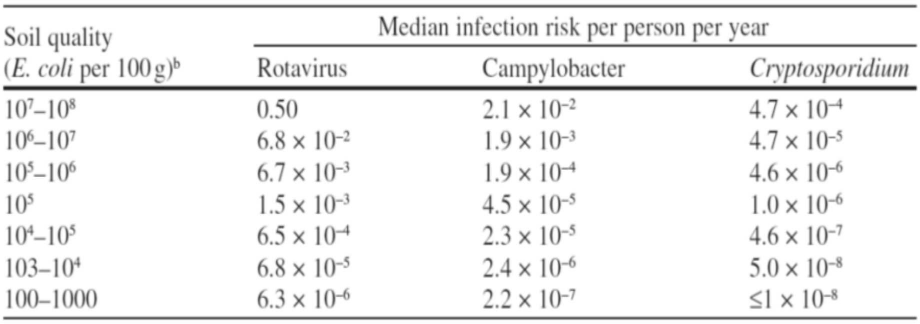
A1.2 Assessing Median Infection Risks in Restricted Irrigation

A1.2.1 Restricted irrigation: refer to irrigation of crops eating cooked:

The model scenario developed for assessing infection risks linked to ingestion of wastewater-saturated soil particles by farmer and field worker, this scenario assume that wastewater-saturated soil may contaminate farmers' or filed workers' fingers and subsequently some pathogens may be transmitted to their mouth and then ingested. Two sub-scenarios are used: the first is highly mechanized agriculture (represented industrialised countries) where tractors and associated equipment are used for plough, sow and harvesting, and farmers and field worker is expected to wear gloves, footwear and other protective clothing when working in wastewater-irrigated fields and .The second is labour-intensive agriculture (represented developing countries) where machines such as tractor are not commonly used and farmer is most likely to not wear gloves, footwear and other protective clothing when working in wastewater-irrigated fields . Table 2,3 give the results of Monte Carlo-QMRA risk analysis for highly mechanized agriculture and labour-intensive agriculture respectively(WHO, 2006)

Restricted irrigation: highly mechanized agriculture with exposure for 100 days per year: median infection risks from ingestion of wastewater-contaminated soil estimated by 10,000-trial Monte Carlo simulations

Table 2: the results of Monte Carlo-QMRA (Restricted irrigation: highly mechanized agriculture)

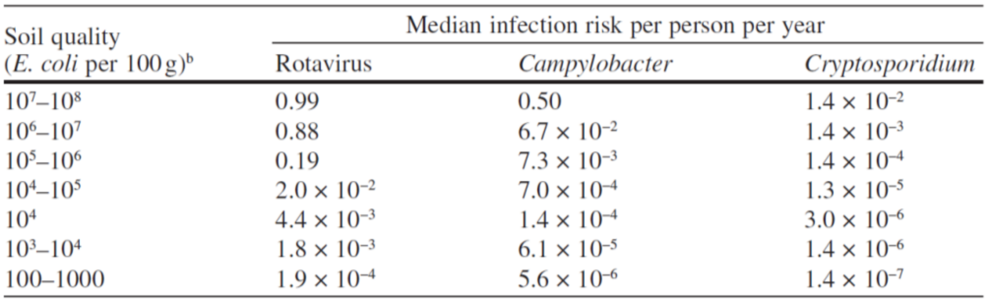


Soil quality	Median infection risk per person per year		
(*E. coli* per 100 g)[b]	Rotavirus	Campylobacter	*Cryptosporidium*
10^7–10^8	0.50	2.1×10^{-2}	4.7×10^{-4}
10^6–10^7	6.8×10^{-2}	1.9×10^{-3}	4.7×10^{-5}
10^5–10^6	6.7×10^{-3}	1.9×10^{-4}	4.6×10^{-6}
10^5	1.5×10^{-3}	4.5×10^{-5}	1.0×10^{-6}
10^4–10^5	6.5×10^{-4}	2.3×10^{-5}	4.6×10^{-7}
103–10^4	6.8×10^{-5}	2.4×10^{-6}	5.0×10^{-8}
100–1000	6.3×10^{-6}	2.2×10^{-7}	$\leq 1 \times 10^{-8}$

1–10 mg soil ingested per person per day for 100 days per year; 0.1–1 rotavirus and Campylobacter, and 0.01–0.1 Cryptosporidium oocyst, per 10_5 E. coli; N_{50} = 6.7 ± 25% and α = 0.253 ± 25% for rotavirus; N_{50} = 896 ± 25% and α = 0.145 ± 25% for Campylobacter; r = 0.0042 ± 25% for Cryptosporidium. No pathogen die-off (taken as a worst case scenario). The wastewater quality is taken to be the same as the soil quality (i.e., the soil is assumed, as a worst case scenario, to be saturated with the wastewater).Source:(WHO, 2006)

Restricted irrigation: labor-intensive agriculture with exposure for 300 days per year: median infection risks from ingestion of wastewater-contaminated soil estimated by 10,000-trial Monte Carlo simulations

Table 3: the results of Monte Carlo-QMRA (Restricted irrigation: labour-intensive agriculture)



Soil quality	Median infection risk per person per year		
(*E. coli* per 100 g)[b]	Rotavirus	*Campylobacter*	*Cryptosporidium*
10^7–10^8	0.99	0.50	1.4×10^{-2}
10^6–10^7	0.88	6.7×10^{-2}	1.4×10^{-3}
10^5–10^6	0.19	7.3×10^{-3}	1.4×10^{-4}
10^4–10^5	2.0×10^{-2}	7.0×10^{-4}	1.3×10^{-5}
10^4	4.4×10^{-3}	1.4×10^{-4}	3.0×10^{-6}
10^3–10^4	1.8×10^{-3}	6.1×10^{-5}	1.4×10^{-6}
100–1000	1.9×10^{-4}	5.6×10^{-6}	1.4×10^{-7}

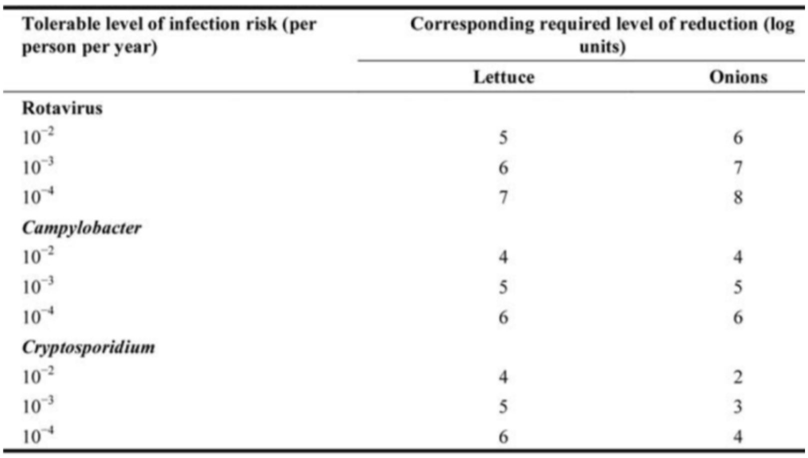
1–10 mg soil ingested per person per day for 300 days per year; 0.1–1 rotavirus and Campylobacter, and 0.01–0.1 Cryptosporidium oocyst, per 10_5 E. coli; N_{50} = 6.7 ± 25% and α = 0.253 ± 25% for rotavirus; N_{50} = 896 ± 25% and α = 0.145 ± 25% for Campylobacter; r = 0.0042 ± 25% for Cryptosporidium. No pathogen die-off (taken as a worst case scenario). The wastewater quality is taken to be the same as the soil quality (i.e., the soil is assumed, as a worst case scenario, to be saturated with the wastewater). Source:(WHO, 2006)

It can be seen that the median risks for Campylobacter and Cryptosporidium in both scenarios are l lower than those for rotavirus. For highly mechanized agriculture from the result in table 2. Tt can be seen that the median rotavirus infection risk is ~10^{-3} pppy for a wastewater quality of 10^5 E. coli per 100 mL. Therefore, a 3-log unit reduction, from 10^7–10^8 to 10^4–10^5 E. coli per 100 mL, is required to achieve the tolerable rotavirus infection risk of 10^{-3} pppy. Whlie table 3 shows that for labour-intensive agriculture 4-log reduction from 10^7–10^8 to 10^3–10^4 E. coli per 100 mL is required to achieve the tolerable rotavirus infection risk of 10^{-3} pppy(WHO, 2006)

A.1.2.2 Unrestricted irrigation: consumption of wastewater-irrigated crops that eaten uncooked (the guidelines used lettuce and onions for non-root crop and root crop respectively).

For unrestricted irrigation different approach was adopted in the guidelines, the Monte Carlo QMRA determined the required total pathogen reduction for different levels of annual infection risk. The results is given in table 4. it can be seen from the table the required pathogen reduction are 6-log and 7- log for non-root crops and root crops respectively in order to achieved tolerable rotavirus annual risk of 10^{-3}

Table 4: Unrestricted irrigation: required pathogen reductions for various levels of tolerable risk of infection from the consumption of wastewater irrigated lettuce and onions estimated by 10,000-trial Monte Carlo simulations



Tolerable level of infection risk (per person per year)	Corresponding required level of reduction (log units)	
	Lettuce	Onions
Rotavirus		
10^{-2}	5	6
10^{-3}	6	7
10^{-4}	7	8
Campylobacter		
10^{-2}	4	4
10^{-3}	5	5
10^{-4}	6	6
Cryptosporidium		
10^{-2}	4	2
10^{-3}	5	3
10^{-4}	6	4

100 g lettuce and onions eaten per person per 2 days; 10–15 mL and 1–5 mL wastewater remaining after irrigation on 100 g lettuce and 100 g onions, respectively; 0.1–1 and 1–5 rotavirus per 10^5 E. coli for lettuce and onions, respectively, N50 = 6.7 ± 25% and α = 0.253 ± 25% for rotavirus; N50 = 896 ± 25% and α = 0.145 ± 25% for Campylobacter; r = 0.0042 ± 25% for Cryptosporidium Assuming the raw wastewater quality to be 10^7–10^8 E. coli per 100 mL

References

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MATHERS, C. D., STEIN, C., MA FAT, D., RAO, C., INOUE, M., TOMIJIMA, N., BERNARD, C., LOPEZ, A. D. & MURRAY, C. J. 2002. Global Burden of Disease 2000: Version 2 methods and results. Geneva: World Health Organization.

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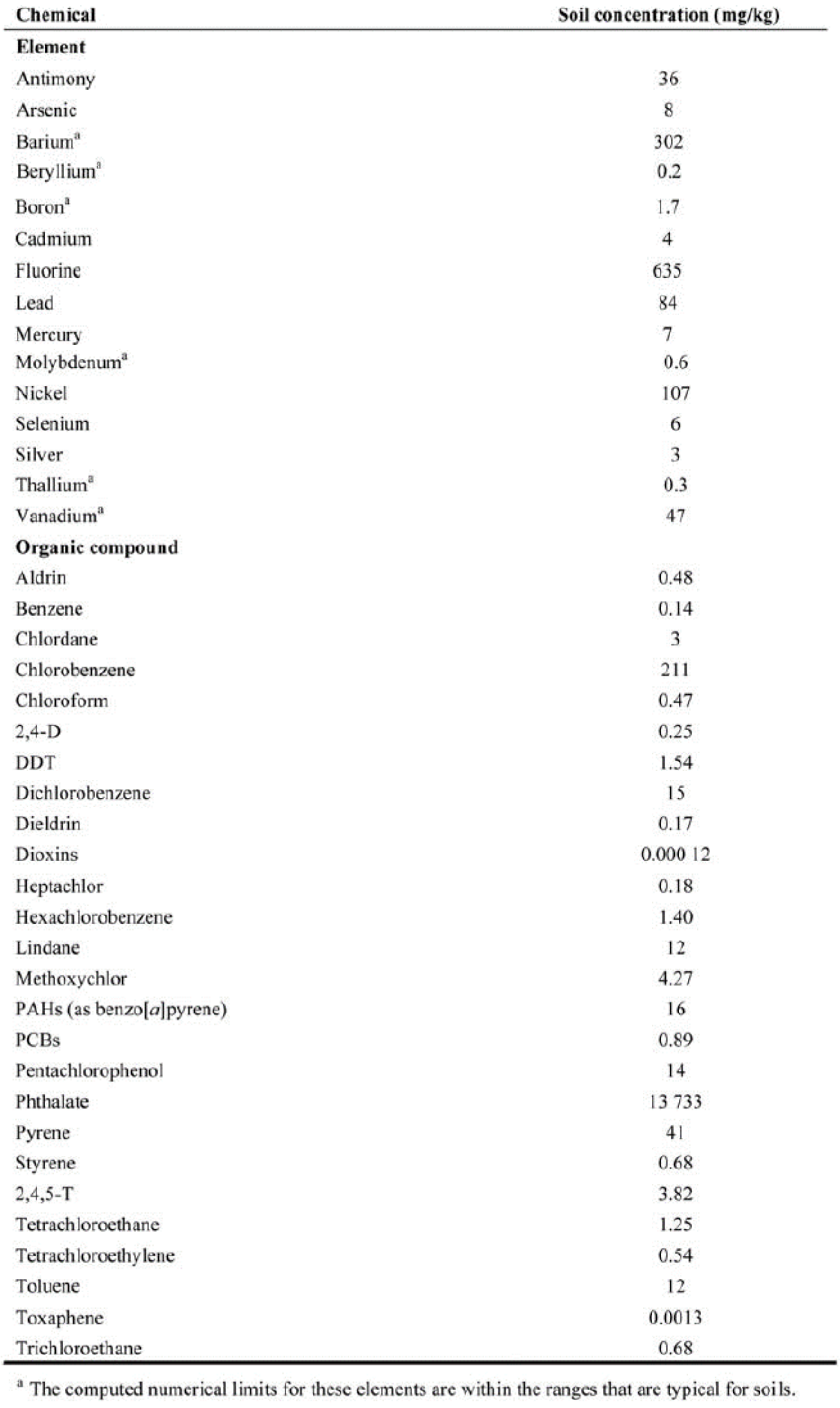
Annex 2

Quality standards for good irrigation

Maximum tolerable concentrations of pollutants in wastewater-irrigated soils[6]



Chemical	Soil concentration (mg/kg)
Element	
Antimony	36
Arsenic	8
Barium[a]	302
Beryllium[a]	0.2
Boron[a]	1.7
Cadmium	4
Fluorine	635
Lead	84
Mercury	7
Molybdenum[a]	0.6
Nickel	107
Selenium	6
Silver	3
Thallium[a]	0.3
Vanadium[a]	47
Organic compound	
Aldrin	0.48
Benzene	0.14
Chlordane	3
Chlorobenzene	211
Chloroform	0.47
2,4-D	0.25
DDT	1.54
Dichlorobenzene	15
Dieldrin	0.17
Dioxins	0.000 12
Heptachlor	0.18
Hexachlorobenzene	1.40
Lindane	12
Methoxychlor	4.27
PAHs (as benzo[*a*]pyrene)	16
PCBs	0.89
Pentachlorophenol	14
Phthalate	13 733
Pyrene	41
Styrene	0.68
2,4,5-T	3.82
Tetrachloroethane	1.25
Tetrachloroethylene	0.54
Toluene	12
Toxaphene	0.0013
Trichloroethane	0.68

[a] The computed numerical limits for these elements are within the ranges that are typical for soils.

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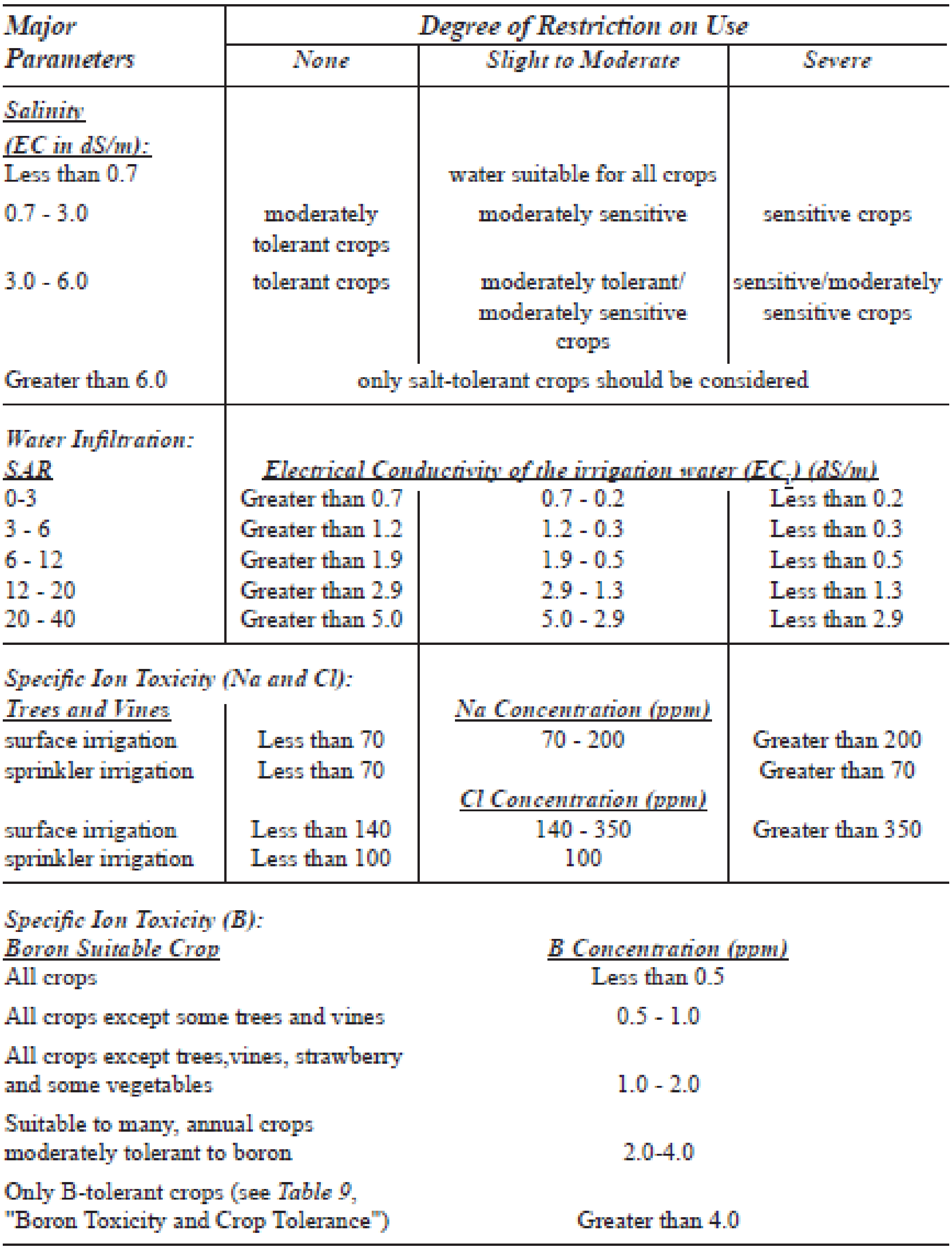
[6] Source: WHO 2006. *Guidelines for the Safe Use of Wasterwater Excreta and Greywater, volume2: wastewater use in agriculture,* World Health Organisation,Geneva.

Water quality guideline for irrigation[7]



Major Parameters	*Degree of Restriction on Use*		
	None	*Slight to Moderate*	*Severe*
Salinity *(EC in dS/m):*			
Less than 0.7		water suitable for all crops	
0.7 - 3.0	moderately tolerant crops	moderately sensitive	sensitive crops
3.0 - 6.0	tolerant crops	moderately tolerant/ moderately sensitive crops	sensitive/moderately sensitive crops
Greater than 6.0	only salt-tolerant crops should be considered		
Water Infiltration:			
SAR	*Electrical Conductivity of the irrigation water (EC_i) (dS/m)*		
0-3	Greater than 0.7	0.7 - 0.2	Less than 0.2
3 - 6	Greater than 1.2	1.2 - 0.3	Less than 0.3
6 - 12	Greater than 1.9	1.9 - 0.5	Less than 0.5
12 - 20	Greater than 2.9	2.9 - 1.3	Less than 1.3
20 - 40	Greater than 5.0	5.0 - 2.9	Less than 2.9
Specific Ion Toxicity (Na and Cl):			
Trees and Vines		*Na Concentration (ppm)*	
surface irrigation	Less than 70	70 - 200	Greater than 200
sprinkler irrigation	Less than 70		Greater than 70
		Cl Concentration (ppm)	
surface irrigation	Less than 140	140 - 350	Greater than 350
sprinkler irrigation	Less than 100	100	
Specific Ion Toxicity (B):			
Boron Suitable Crop		*B Concentration (ppm)*	
All crops		Less than 0.5	
All crops except some trees and vines		0.5 - 1.0	
All crops except trees,vines, strawberry and some vegetables		1.0 - 2.0	
Suitable to many, annual crops moderately tolerant to boron		2.0-4.0	
Only B-tolerant crops (see *Table 9*, "Boron Toxicity and Crop Tolerance")		Greater than 4.0	

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[7] Sources:

WHO 2006. *Guidelines for the Safe Use of Wasterwater Excreta and Greywater, volume2: wastewater use in agriculture*, World Health Organisation,Genev

AYERS, R. S. & WESTCOT, D. W. 1985. *Water quality for agriculture.FAO Irrigation and Drainage Paper . No. 29* Rome.

Annex 3

Review of the burden of Waterborne Disease in Libya which could Impose Risk to Public Health due to Wastewater Irrigation

A3.1 Abstract

The main purpose of this review is to explore the available epidemiological studies for detecting the most endemic and frequent outbreaks Water/Sanitation -related diseases in Libya that seem to have a potential risk on Libyan population from wastewater reuse in Agriculture. Hence, they would be considered in the health risk assessment of reusing wastewater for agriculture propose in Libya. Based on World Health Organisation (WHO, 2009, 2012, 2011) and literature, the most endemic water/ sanitation related diseases are: Diarrhoea, typhoid fever, hepatitis A and E. According to the first WHO report 2010 on neglected tropical diseases, the prevalence of Soil-Transmitted Helminths infection and Schistosomiasis in the Middle East and North Africa countries is relatively l ow with prevalence rate of (<20%) and (<10%) respectively.

Keywords: Water/Sanitation -related diseases, Middle East and North Africa, prevalence of infectious disease, Disease burden

A3.2 Introduction

The use of wastewater can pose substantial risks to human health, especially when untreated or partially treated wastewater is used for crops irrigation(WHO, 2006, Jiménez et al., 2010a). The major risks to public health are microbial risks which arises as results of the infectious pathogens that are normally present in untreated or partially treated wastewater. A variety of human pathogens existing in wastewater can contribute to causing many excreta-related diseases and other diseases (such as vector- borne diseases) to the farmers, consumers of wastewater irrigated crops and nearby communities(WHO, 2006, Scheierling et al., 2010). The concentration and the types of these pathogens (Viruses, bacteria, protozoa and helminths) vary from region to region and over the time. It depends on the background of disease infection levels in the population, for example, the concentration of infectious pathogens can be at the highest level in regions where faecal related diseases are widely endemic. Excreta-related disease outbreaks could also result in an increase the level of causative pathogens in the excreta and wastewater(WHO, 2006). Not all agents in wastewater will cause illness, different agent and exposure route will contribute to different disease burdens. The importance of pathogens in causing infection relay on many factors including the agent's ability to cause disease, their persistence in the environment, the minimum infective dose, latency periods and ability to induce human immunity. Thus, agents with low minimal infective doses and long infectious persistence in the environment as well as long latency periods more likely to have a higher potential for causing disease that the others. According to that, the waterborne diseases infection, where endemic, pose the highest potential risks associated with use wastewater for irrigation purposes(Bos et al., 2010, WHO, 2006). Therefore, for developing risk assessment management strategies associated with the use of wastewater in agriculture, it is very important to identify the most potential infectious-pathogens in wastewater that cause the highest health risk in any specific area. It could be achieved by studying and evaluating the microbial hazard in wastewater simultaneously with epidemiological investigations of prevalent endemic diseases and the history of disease outbreaks in the area.

The main purpose of this review is to explore the available epidemiological studies for detecting the most endemic and frequent outbreaks Water/Sanitation -related diseases in Libya that would be considered in the health risk assessment of reusing wastewater for agriculture propose in Libya. Since, the burden of disease data specific to Libya is a few; the search covered **Middle East** (Bahrain, Iran, Iraq, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Syria, UAE, and Yemen) and **North Africa** (Algeria, Egypt, Libya, Morocco, Tunisia). The research limited to review published from 1980 to 2015, and used terms included: **(water -borne diseases, Vector–borne diseases, infectious diseases, excreta-related disease, burden diseases, Diarrhoeal disease, salmonella disease, hepatitis, typhoid, Enteric Fever, helminths infection, ascariasis, Ascaris, Schistosomiasis, Intestinal parasitic infection**).

A3.3 Results

Based on World Health Organisation (WHO, 2009, 2012, 2011) and limited data in literature; the most endemic water/ sanitation related diseases that seem to have a potential risk on Libyan population from wastewater reuse are Diarrhoea, typhoid fever, hepatitis A and E.

According to the first WHO report in 2010 on neglected tropical diseases, the prevalence of Soil-Transmitted Helminths infection and Schistosomiasis is relatively low in the Middle East and North Africa countries(Hotez et al., 2012, Daumerie et al., 2010).

Studies about intestinal parasites in school pupils aged (5 to 17 years) in different cities in Libya have also indicate that Giardia lamblia is one of the common intestinal parasites among children. Its prevalence range from 1-30%(Bernawi et al., 2013, Kasssem et al., 2007, Ben et al., 2007, Al Kilani et al., 2008).

Vector–borne diseases such as Malaria and lymphatic filariasis -that could be associated with the reuse of wastewater for irrigation- are not endemic in Libya (Hotez et al., 2012, Amin et al., 2013, 2009).

Diarrhoea

Diarrhoea remains a major health problem in children worldwide; it is the leading cause of mortality and morbidity among children in developing countries. In 2004 the world health organisation WHO has estimated that diarrhoea caused an estimated 527000 child deaths around the world (Kirk et al., 2015). An updated study in 2012 indicated that in 2010 diarrhoea contribute to 9·9% (0·751 million) of deaths and children under five years of age in developing countries being most affected (Liu et al., Kirk et al., 2015). This disease is a heavy burden in most of the Middle East and North Africa (MENA), recently, it has been estimated that about 65000 deaths annually among children in MENA countries due to diarrhoea ((Malek et al., 2010). In Libya, the diarrhoea is a contributor to 8% of children mortality(WHO, 2011).

In last few decades, number of enteric agents including viruses (e.g., rotavirus, adenovirus , astrovirus and norovirus), bacteria(e.g. salmonella spp, nterohemorrhagic Escherichia coli , and enteroadherent E. coli Campylobacter spp, Shigellas pp, Yersinia enterocolitica and E. coli O157:H7) and protozoa(e.g., Cryptosporidium, Entamoeba histolytic, Giardia lamblia) have been identified as main causes of diarrhoea in human(Ghenghesh et al., 2001, Rahouma et al., 2011, WHO, 2006).

Although published studies regarding the causative agents of childhood diarrhoea in Libya are very few, the available data from literature indicate that rotavirus is the leading cause of severe diarrhoea in Libyan children. Followed by bacteria non-typhoid salmonella(Ali et al., 2005, Ghenghesh et al., 2001, Ghenghesh KS et al., 2008, Malek et al., 2010, Rahouma et al., 2011, Khoury et al., 2011).

In 2010, a systematic review of studies of rotavirus diarrhoea in MEAN regions carried by Malek et al. shows that about 40% of Children hospitalised for diarrhoea were more likely to have rotavirus detected (Malek et al., 2010). All the studies that have been reviewed on the causative pathogens of acute children diarrhoea in Libya agree on Rotavirus is the major cause of acute diarrhoea. The overall rate of occurrence varies from 13% to 34% of the total diarrhoeal cases(Ghenghesh et al., 2001, Ghenghesh KS et al., 2008, Malek et al., 2010, Rahouma et al., 2011, Khoury et al., 2011). According to WHO, the annual mortality rate per 100,000 child under five years of age due to rotavirus in the Libya is 14% (Khoury et al., 2011). Non-typhoid Salmonella is considered in the literature as a second major cause of acute diarrhoea among Libyan children, the prevalence rate of the salmonella from different cities ranges from 6% to 19%(Ghenghesh et al., 2001, Ghenghesh KS et al., 2008, Rahouma et al., 2011, Ali et al., 2005).

In addition to rotavirus and Salmonella, norovirus, Campylobacter and Cryptosporidium also play an important role in the aetiology of children diarrhoea in Libya (Ghenghesh et al., 2001, Ghenghesh KS et al., 2008, Ali et al., 2005). While rotavirus leading cause of acute childhood diarrhoea, Noroviruses are considered to be the most common cause of non-bacterial gastroenteritis affecting both children and adults worldwide(Ushijima et al., 2014, Widdowson et al., 2005, Patel et al., 2008, Matthews et al., 2012). Two studies were carried in Tripoli 2008 reported for the first time that norovirus is also a predominant agent found in diarrheic children with rate 15.5% and 17.5% (Rahouma et al., 2011, Abugalia et al., 2011). Enteropathogenic Escherichia coli EPEC prevalence rate range from 4% to 11% (Ghenghesh KS et al., 2008, Rahouma et al., 2011).

Typhoid fever

Typhoid fever continues to be an important cause of morbidity and mortality among children and young adults worldwide. The last global burden of disease estimates in 2010 for typhoid and paratyphoid fever reported that the disease was estimated to cause about 25.8 million cases of illness and 178,215 deaths in the world(Kirk et al., 2015). Typhoid fever has been estimated to cause about 20.9 million cases of illness in the world(Kirk et al., 2015). Typhoid fever is acute infection mainly caused by Salmonella enteric serotype Typhi (Salmonella typhi)(Ghenghesh et al., 2009).

This disease is endemic in many developing countries including the Middle East and North African countries. The available date regard to the typhoid fever incident in North Africa is limited mainly due to the absent or insufficient epidemiological surveillance activities and lack of diagnostic facilities. However, a medium incidence of 10 to 100 cases per 100,000 persons in North African has been estimated(Bhan et al., Srikantiah et al., 2006, Ghenghesh et al., 2009). According to recent estimates of the Global and Regional Disease Burden in 2010 supported by the WHO the burden of typhoid and paratyphoid fever in Eastern Mediterranean Region (including the Middle East and North African countries except Algeria) is 25 cases per 100,000 (Kirk et al., 2015). The burden of the disease is associated with inadequate sanitation and access to unsafe water and food, which the outbreaks caused by Salmonella Typhi is mainly as a result of consumption of untreated or sewage-contaminated water(Ghenghesh et al., 2009).

In Libya, during a period of 5 years from 1975, a comprehensive study was conducted on 30,165 hospitalised patients with acute diarrhoea. A prevalence of S. Typhi in patients was detected only 81 case of S. Typhi infection from 30,165 patients. In last few years, an increased rate of typhoid fever has been reported. According to the Libyan Centre for Information and Documentation (CID) of the Secretary of Health and Environment, the incidence rate has been increased from seven per 100,000 of the population in 2004 to 16 case per 100,000 of the population in 2006. However, this information is based only on clinical feature without any laboratory confirmation. The significant increase in the incidence since the 1980s is claimed to be due to the improved facilities in local health care for diagnosing the cases and the improvement of data reporting system(Ghenghesh et al., 2009).

Hepatitis A and E

Viral hepatitis A B C D and E represents an important health issue in the North African countries(, Egypt, Libya, Tunisia, Algeria and Morocco. The epidemiology of viral hepatitis in North Africa is dynamic and influenced by many factors including hygiene, socioeconomic status (Kamal et al., 2010). This review will only explore the epidemiology of viral hepatitis A and E since they are excreta- related diseases, in North Africa with more focus on Libya.

Hepatitis A Virus HAV

HAV remain a public health problem in The Middle East and North African countries which is considered as high HAV prevalence area with a rate of 237 illness per 100,000 (Kamal et al., 2010, WHO, 2000, Kirk et al., 2015). Even the mortality rate as a result of hepatitis A is low; it is a significant cause of morbidity worldwide(FitzSimons et al., 2010). The main transmission routes of the HAV infection is through faecal oral transmission by consuming contaminated food or drinking polluted water (Kamal et al., 2010, WHO, 2000, Jeong and Lee, 2010). This infection is characterised by a lifetime risk of infection higher than 90% in the region(Kamal et al., 2010).

Most of the studies on the prevalence of Hepatitis in Libya focus on HCV and HBV. An early survey conducted into sites in Libya have indicated that most HAV in Libya infections are acquired early in life between 5-15 years, and most of who infected could not experience any noticeable symptoms. Survey also revealed that HAV antibodies could be detected in 60-70% of children age of 3 years. By the age of 7 years, nearly 100% of children are HAV immune(Gebreel and Christie, 1983).

More recent studies carried in neighbour country Tunisia reported that the prevalent rate of HAV range between 84% to 92% in Tunisia and the infection is progressively shifting to older ages(Rezig et al., 2008, Gharbi- Khelifi et al., 2007, Letaief et al., 2005). A survey was carried to assess the occurrence of HAV among children and adolescents showed that overall prevalence among children <15 years of age was 60%, and 83% in those > 15 years of ages(Letaief et al., 2005)

Hepatitis E virus HEV

Hepatitis E virus HEV previously known as epidemic non-A, non-B hepatitis(Meng, 2010).This enteric transmitted virus is endemic in most of developing the world especially in countries where drinking water resources are contaminated with human waste(Kamal et al., 2010, WHO, FitzSimons et al., 2010). Traditionally, hepatitis E has been considered a short-lived and self-limiting viral infection followed by recovery. The infection incidence is typically higher in juveniles and adults between the ages of 15 and 40 that in young children(Meng, 2010, FitzSimons et al., 2010), it is recognised as important leading causes of acute hepatitis in adults in North Africa. Mortality rates due to HEV are generally low (Kamal et al., 2010, WHO, FitzSimons et al., 2010). However, on some occasion, fulminant hepatitis could develop, with overall infected population particularly among pregnant women and Patients with chronic liver disease(FitzSimons et al., 2010). Mortality rates range from 0.5% to 4.0%, mostly associated with older age 50 years in North African countries(FitzSimons et al., 2010, Kamal et al., 2010), this rate increase to 20% among pregnant women in the third trimester(Kamal et al., 2010). Despite the high prevalence rates of HEV in North African countries, HEV infection in the region is hard to be symptomatic and uncommon to develop fulminant hepatitis(Kamal et al., 2010).

An accurate estimation of the prevalent rate of HEV in Libya is not available. However, the prevalent rates from the other countries in the region could be as an approximate indicator of the rate in Libya. The prevalent rates of HEV in Tunisia is 4.3%, and it has been reported that there is no epidemics attributed to HEV in Tunisia suggesting that the virus could be circulating among the Tunisian population as sporadic cases(Rezig et al., 2008). In Morocco the prevalent rates estimated to be between 6.0% to 10.4% (Benjelloun et al., 1997).

Overall Hepatitis A and E are endemic in the North African countries. Despite the essentially subclinical features of the infections in the residential population, HAV and HEV could represent a high risk to expatriates and tourists visiting. These countries consequently increase the risk of an outbreak of these disease in non-endemic areas (Marano and Freedman, 2009, Jeong and Lee, 2010, MacDonald et al., 2013, FitzSimons et al., 2010, Kamal et al., 2010)

Ascariasis

In general Soil-Transmitted Helminths, infections are common in and representing only 1-3% of the global disease burden. The prevalence of is vary from High (prevalence ≥50%) in Yemen, Moderate (prevalence 20%–49%) in Egypt to relatively low (<20% prevalence) in the rest of the region. (Hotez et al., 2012, Daumerie et al., 2010). The most common Soil-Transmitted Helminths infection the Middle East and North Africa countries are ascariasis with estimated cases of 23 million cases followed by 9 million cases of trichuriasis and 4–5 million cases of hookworm infection(De Silva et al., 2003). Among these countries, Egypt leads in the number of 8.3 million cases of ascariasis followed by Yemen, 5.8 million Iran, 5.1 million and Morocco, 1.3. Million(De Silva et al., 2003).

Although there are not estimates of the number of cases in Libya, updated data indicated that in 2010 Median rate per 100,000 of ascariasis in the Middle East and North Africa countries is be 200 cases with 0.02 deaths(Torgerson et al., 2015).

A few studies in Libya on intestinal parasites in school pupils aged (5 to 17 years) indicated that the overall prevalence of Ascaris lumbricoides infection among children is range from absent to 35.5% (Ben Musa, 2007, Kasssem et al., 2007, Ben et al., 2007, Al Kilani et al., 2008, Sadaga and Kassem, 2007, Jacobsen et al., 2007). In Libya Ascariasis are generally associated with lack of education, low socioeconomic status, and family size(Sadaga and Kassem, 2007)

Schistosomiasis

Schistosomiasis (or bilharzia) is an important waterborne parasitic disease, caused by Schistosoma spp, it is endemic in 52 developing countries worldwide with the moderate and high transmission, in 2013 at least 261 million are estimated to require preventive treatment (WHO). Part of Yemen this disease reported to have low prevalence rate (<10%) in Middle East and North African countries MENA(Hotez et al., 2012, Daumerie et al., 2010). However, Libya ranks the fourth place in number of schistosomiasis cases in MENA countries after Egypt, Yemen and Algeria; it is estimated that in 2006 around 0.3 million cases of Schistosomiasis in Libya(Hotez et al., 2012)

Date on the burden of schistosomiasis in Libya is limited and mostly is not up to date. Nevertheless, an official report of inter-country meeting of Eastern Mediterranean countries in Oman 2007 claimed that infection of Schistosoma has been reported in certain places in Libya since 1925, one of these places is Tourga town (50Km south-east the case study of Misurata)(WHO, 2007).The same report indicates that disease has been reported frequency from Tourga community since 1957. In 1998 Schistosoma- Masoni prevalent rate in the town was 21.9% and among school children was 28.9%, the latter has increased significantly to 55% in 1999(WHO, 2007). In last few years, the prevalent rate has been reported to be decreased sharply after enforcement of control activities such as screening of total population, free treatment, snail control and awareness raising of the endemic population(WHO, 2007).

A3.4 Conclusion

Using untreated or partially treated wastewater could contribute to microbial risk leads to outbreaks disease among farmers and consumer and nearby community. Identifying the most burden diseases and related pathogens is the first step of health risk assessment of using wastewater in agriculture.

Due to the absence of national health information and limited studies in the prevalence of waterborne disease in Libya, literature from North Africa and the Middle East was reviewed to investigate the most endemic waterborne disease in Libya. Based on World health organisation and limited literature from the Middle East and North Africa, the potential significant health risks on Libyan population from wastewater reuse in agriculture could mainly come from Diarrhoea and Typhoid Fever and followed by, Hepatitis A&E Ascariasis and Schistosomiasis.

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Annex 4

Modelling Tool for Evaluating Wastewater Reuse Options for Agricultural Purposes

Authors: Manal Elgallal, Louise Fletcher, and Barbara Evans

The purpose of this tool is to help decision- maker to select the most effective wastewater management option(s) for reuse in agriculture

This tool combine three aspect:

1. **Model for Environmental risk assessment**: assessing different wastewater reuse option for salinity and excessive nitrogen management.
2. **Model for Health Risk Assessment**: which incorporate the results of Quantitative Microbial Risk Assessment and Monte Carlo computer program MC-QMRA.
3. **Model for Costs -Benefits Analysis**: calculating life cycle costs and potential benefits of wastewater reuse strategies to decide which of these management strategies are economically justified

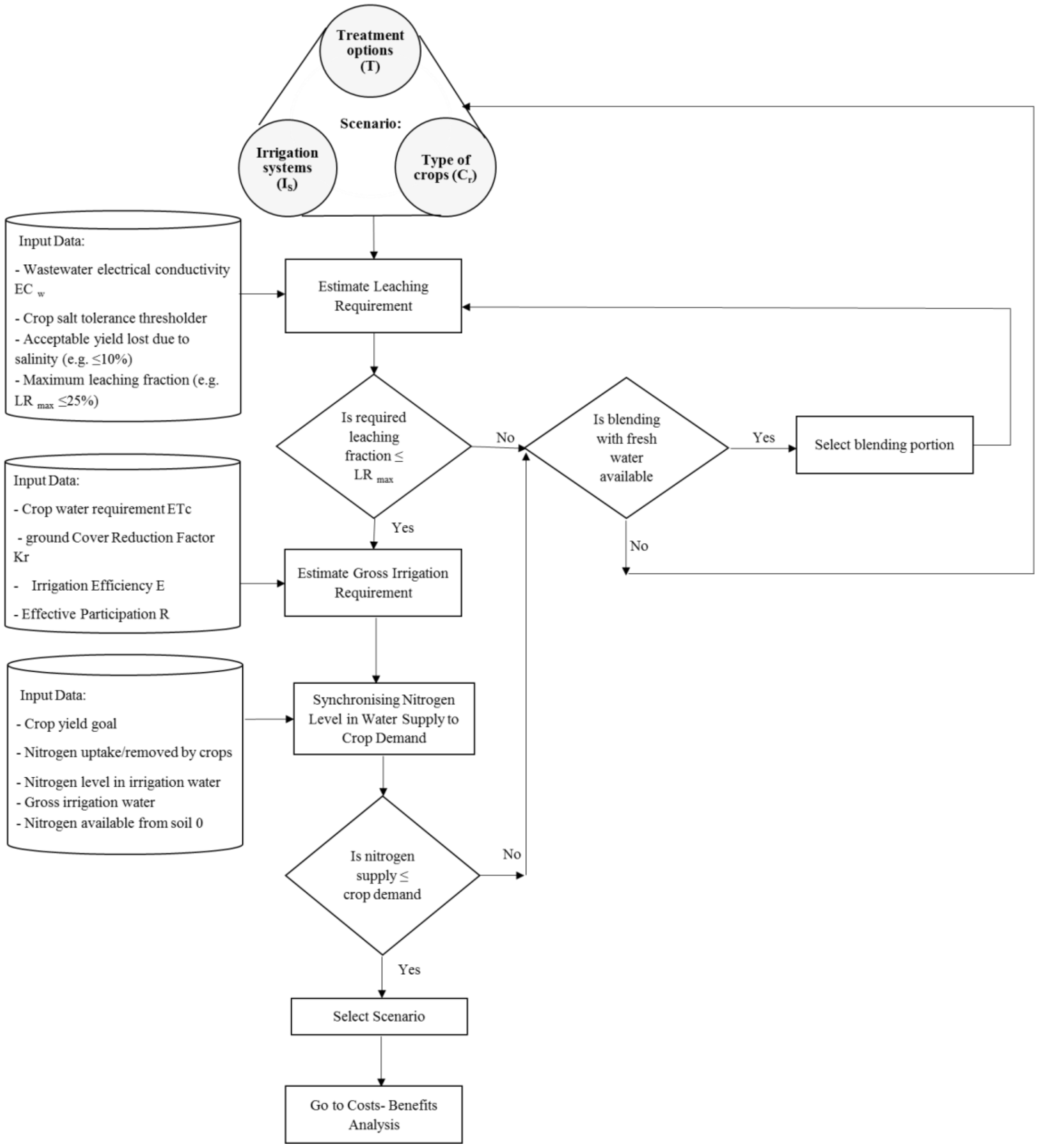
PLEASE NOTE: This is planning tool should NOT be used for detailed risk assessment, costing and design purposes. Thus, numeric values that generated only provide a broad indication for comparing and prioritizing agricultural activities and wastewater management strategies. Users may need to estimate some key data required by the tool and should be aware that the results are only indicative and dependent on the quality of the data input

How to Use:

For each of above models the tool divided into 4 sections, **Input Data**, **Variable**, **Calculations**, and **Results**

MODEL 1: Environmental Risk Assessment

This includes: Key input data for salinity management, excessive nutrient management and fertiliser demand. The next diagram provide the flowchart of environmental risk assessment.



Flowchart for assessment of environmental risk management strategies

1- Salinity management

Estimate Leaching requirement

Leaching requirement in this research was estimated using the traditional approach (Rhoades, 1974, Ayers and Westcot, 1985, Hoffman, 1985) which is widely used in the literature for the design and management of irrigation systems and wastewater land application (Hillel, 2000, Simmons et al., 2010, Minhas, 1996, Duan et al., 2011b, Hanson et al., 1999) . The approach assumed that steady-state conditions exist over long periods and are based on simple salt-balance concepts, with some modifications to account for salt precipitation and dissolution reactions. Therefore the minimum leaching fraction can be calculated using the following equations

Surface and sprinkle irrigation

$$LR'_{Cr} = \frac{ECw}{[5ECe - ECw]} \qquad \text{Equation 1}$$

Drip irrigation:

$$LR_{Cr} = \frac{ECw}{2\ x\ [maxECe]} \qquad \text{Equation 2}$$

Where:

- LR'_{Cr}= minimum leaching requirement fraction needed to control salts within the tolerance (ECe) of the crop (C_r)
- ECw = electrical conductivity of irrigation water (dS/m or mmhos/cm)
- ECe = electrical conductivity of saturated soil extract that tolerated by the crop (dS/m or mmhos/cm).It is recommended that the ECe value that can be expected to result in at least a 90% or greater yield be used in the calculation.
- maxECe = electrical conductivity of saturated soil extract that will reduce the crop yield to zero (dS/m or mmhos/cm)

The salt tolerance data that was used to calculate the leaching fraction, which is expressed as the electrical conductivity of saturated soil, was extracted from Maas and Grattan (1999) and based on the following equation

$$Y=100 - B\ (ECe - MinECe) \qquad \text{Equation 3}$$

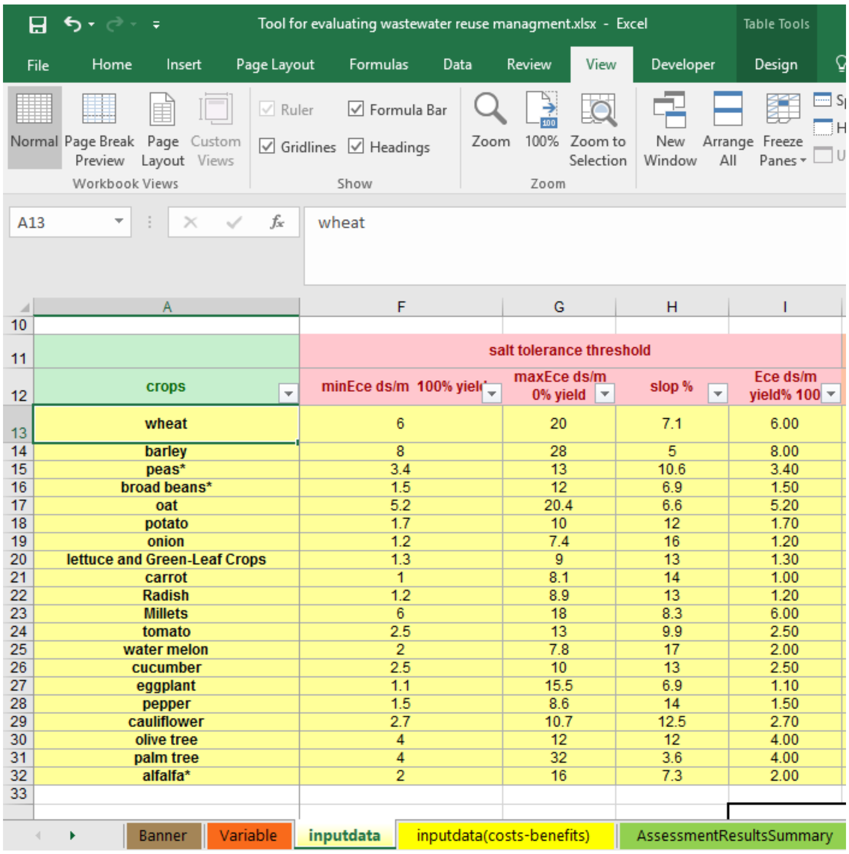
Where:

- Y = Relative yield or yield potential (%)
- MinECe = Threshold value (dS/m) of root zone salinity at which 100% yield occurs
- B = Slope of linear line (% reduction in relative yield per increase in soil salinity, dS/m), and
- ECe = Average root zone soil salinity (dS/m).

Data input for leaching requirement

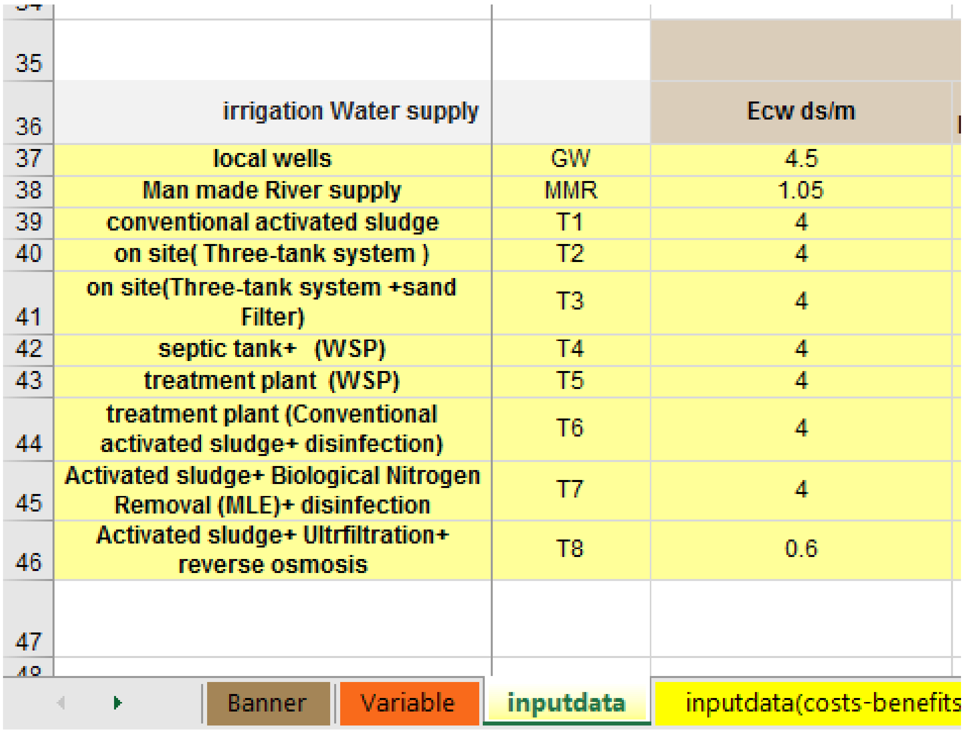
What you have to do now is to choose list of potential corps and their salt tolerance threshold and irrigation water supply options (fill in the yellow cells)

In Data Input Sheet this is what you see for the leaching requirement data input:



A13 wheat

	A	F	G	H	I
10					
11		salt tolerance threshold			
12	crops	minEce ds/m 100% yiel	maxEce ds/m 0% yield	slop %	Ece ds/m yield% 100
13	wheat	6	20	7.1	6.00
14	barley	8	28	5	8.00
15	peas*	3.4	13	10.6	3.40
16	broad beans*	1.5	12	6.9	1.50
17	oat	5.2	20.4	6.6	5.20
18	potato	1.7	10	12	1.70
19	onion	1.2	7.4	16	1.20
20	lettuce and Green-Leaf Crops	1.3	9	13	1.30
21	carrot	1	8.1	14	1.00
22	Radish	1.2	8.9	13	1.20
23	Millets	6	18	8.3	6.00
24	tomato	2.5	13	9.9	2.50
25	water melon	2	7.8	17	2.00
26	cucumber	2.5	10	13	2.50
27	eggplant	1.1	15.5	6.9	1.10
28	pepper	1.5	8.6	14	1.50
29	cauliflower	2.7	10.7	12.5	2.70
30	olive tree	4	12	12	4.00
31	palm tree	4	32	3.6	4.00
32	alfalfa*	2	16	7.3	2.00
33					



35			
36	irrigation Water supply		Ecw ds/m
37	local wells	GW	4.5
38	Man made River supply	MMR	1.05
39	conventional activated sludge	T1	4
40	on site(Three-tank system)	T2	4
41	on site(Three-tank system +sand Filter)	T3	4
42	septic tank+ (WSP)	T4	4
43	treatment plant (WSP)	T5	4
44	treatment plant (Conventional activated sludge+ disinfection)	T6	4
45	Activated sludge+ Biological Nitrogen Removal (MLE)+ disinfection	T7	4
46	Activated sludge+ Ultrfiltration+ reverse osmosis	T8	0.6
47			

Estimate Gross Irrigation Requirement

The gross irrigation requirement was calculated using the following formula:

$$TR_{Cr} = \left(\frac{ETc-R}{E}\right)/(1- LR'_{Cr}) \qquad \text{Equation 4}$$

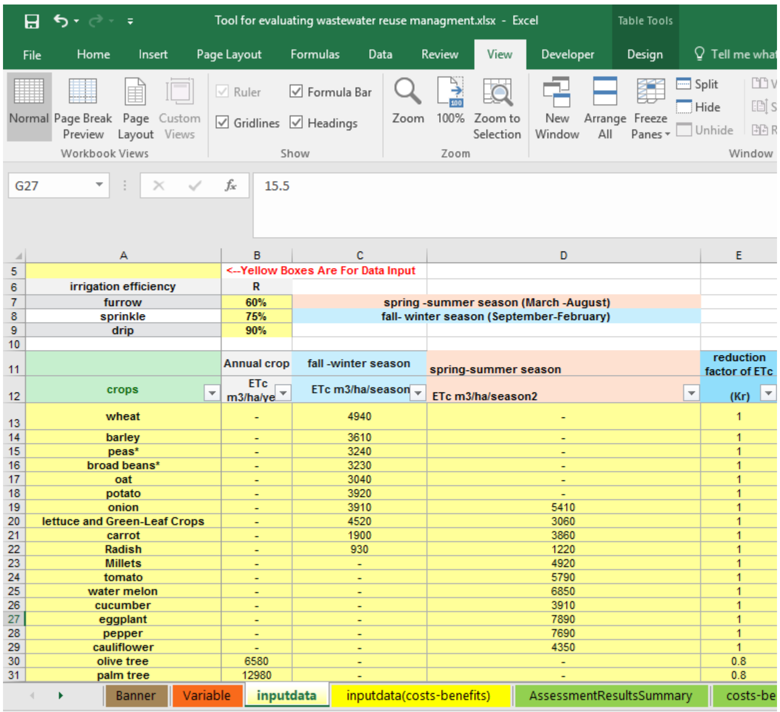
Where:

- ETc = crop water requirement per unit area (m^3/ha/Season)
- R = effective Precipitation
- E = Irrigation Efficiency

For estimating crop water requirement per unit area (m^3/ha/Season)(ETc) estimation another software needed to be used, in this study the CROPWAT software with Penman–Monteith equation was used to estimate ETc (Allen et al., 1998)

Data Input for Gross Irrigation Requirement

IN Data Input Sheet This is what you see for Gross Irrigation Requirement data input



	A	B	C	D	E
5		<--Yellow Boxes Are For Data Input			
6	irrigation efficiency	R			
7	furrow	60%	spring -summer season (March -August)		
8	sprinkle	75%	fall- winter season (September-February)		
9	drip	90%			
10					
11		Annual crop	fall -winter season	spring-summer season	reduction factor of ETc
12	crops	ETc m3/ha/ye	ETc m3/ha/season	ETc m3/ha/season2	(Kr)
13	wheat	-	4940	-	1
14	barley	-	3610	-	1
15	peas*	-	3240	-	1
16	broad beans*	-	3230	-	1
17	oat	-	3040	-	1
18	potato	-	3920	-	1
19	onion	-	3910	5410	1
20	lettuce and Green-Leaf Crops	-	4520	3060	1
21	carrot	-	1900	3860	1
22	Radish	-	930	1220	1
23	Millets	-	-	4920	1
24	tomato	-	-	5790	1
25	water melon	-	-	6850	1
26	cucumber	-	-	3910	1
27	eggplant	-	-	7890	1
28	pepper	-	-	7690	1
29	cauliflower	-	-	4350	1
30	olive tree	6580	-	-	0.8
31	palm tree	12980	-	-	0.8

NOTE:

- **in this study effective rainfall was included in estimating ETc**
- **Kr is a reduction factor in the case of using drip irrigation system.** the overall ETc would be expected to be less under drip irrigation as the irrigation is much more localised and therefore only a portion of soil around the plant is wetted. For drip irrigation systems, ETc is reduced accordingly using a ground cover reduction factor, Kr (Savva and Frenken, 2002)

2- Synchronizing nutrients (N,P&K) application rates to the crops demand and fertiliser demand

Although the main focus is to manage excessive nitrogen, the tool capable to estimate the application rates to synchronise the main nutrients contains in water supply.

- Crop nutrient requirement= crop nutrient removal (kg/ton)× crop yields (ton/ha) Equation 5
- $\boldsymbol{nutrients\ \ from\, wastewater} \left(\frac{\boldsymbol{kg}}{\boldsymbol{ha}}\right) = \boldsymbol{nutrient\ consentration} \frac{\boldsymbol{mg}}{\boldsymbol{l}} * \mathbf{10^{-3}} \times \boldsymbol{TR_{Cr}}\ (\boldsymbol{m^3/ha})$ Equation 0-1
- Chemical Fertiliser demands(ton/ha) =

Σ[(crop nutrient requirment $\left(\frac{\text{kg}}{\text{ha}}\right)$ − nutrients from wastewater $\left(\frac{\text{kg}}{\text{ha}}\right)$ − nutrient available from soil $\left(\frac{\text{kg}}{\text{ha}}\right)$ − nutrient in applyied manure (kg/ha]. Equation 6

Nutrient in Manures application=

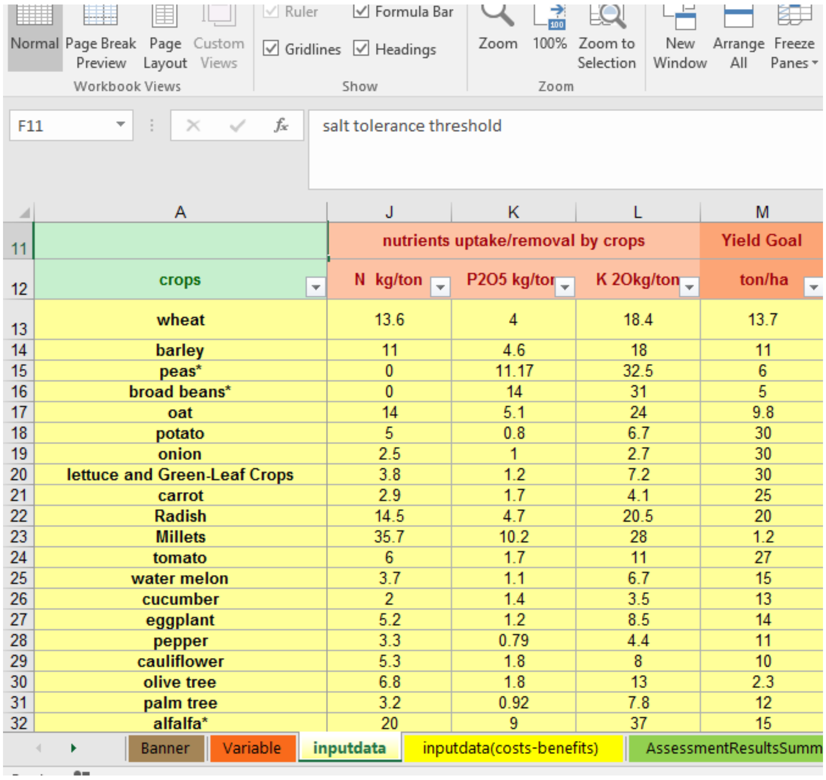
$$\frac{\boldsymbol{amount\ of\ manure}\times\boldsymbol{nutrient\ available\ in\ first\ year}\ (\mathbf{1}-\%\boldsymbol{loss})\times\boldsymbol{nutrient\ in\ manure}\ \%}{\mathbf{100}}$$

Equation 7

Data input

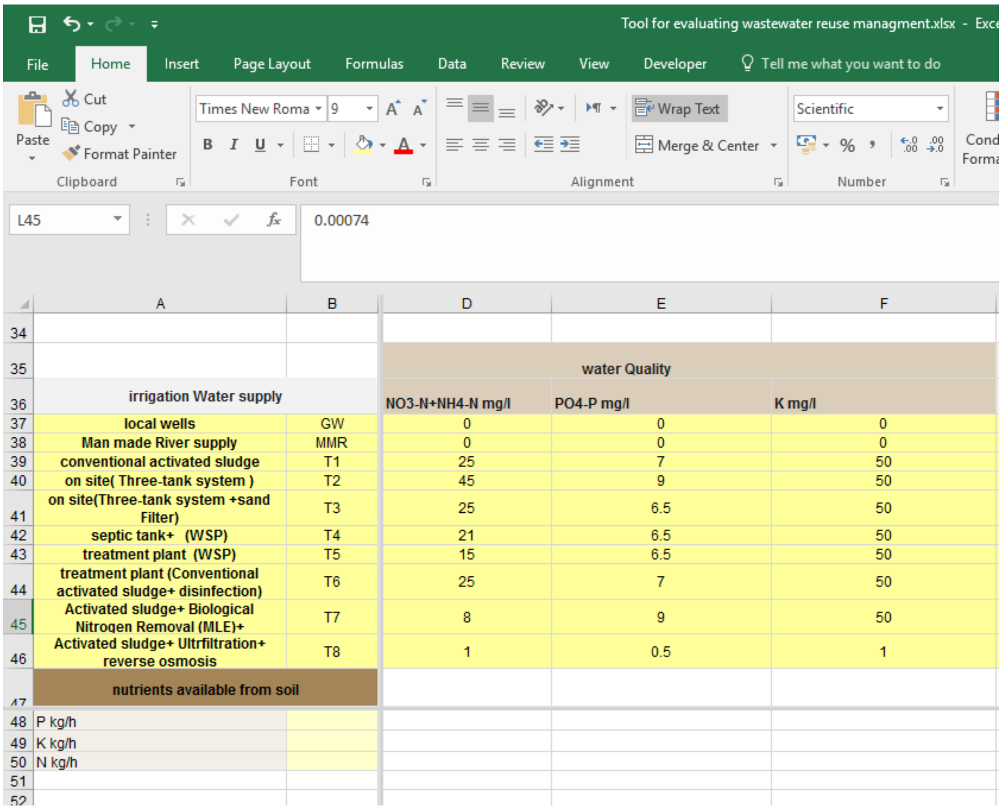
Data input includes: crops nutrient uptake/remove, yield Goal, nutrients concentration in wastewater nutrient in soil, manures, and chemical fertilisers (**fill the yellow calls**)

In Data Input Sheet This is what you see for Synchronizing nutrients (N,P&K) application rates to the crops demand and chemical fertiliser demand



F11 salt tolerance threshold

	A	J	K	L	M
11		nutrients uptake/removal by crops			Yield Goal
12	crops	N kg/ton	P2O5 kg/ton	K 2Okg/ton	ton/ha
13	wheat	13.6	4	18.4	13.7
14	barley	11	4.6	18	11
15	peas*	0	11.17	32.5	6
16	broad beans*	0	14	31	5
17	oat	14	5.1	24	9.8
18	potato	5	0.8	6.7	30
19	onion	2.5	1	2.7	30
20	lettuce and Green-Leaf Crops	3.8	1.2	7.2	30
21	carrot	2.9	1.7	4.1	25
22	Radish	14.5	4.7	20.5	20
23	Millets	35.7	10.2	28	1.2
24	tomato	6	1.7	11	27
25	water melon	3.7	1.1	6.7	15
26	cucumber	2	1.4	3.5	13
27	eggplant	5.2	1.2	8.5	14
28	pepper	3.3	0.79	4.4	11
29	cauliflower	5.3	1.8	8	10
30	olive tree	6.8	1.8	13	2.3
31	palm tree	3.2	0.92	7.8	12
32	alfalfa*	20	9	37	15



Tool for evaluating wastewater reuse managment.xlsx - Exce

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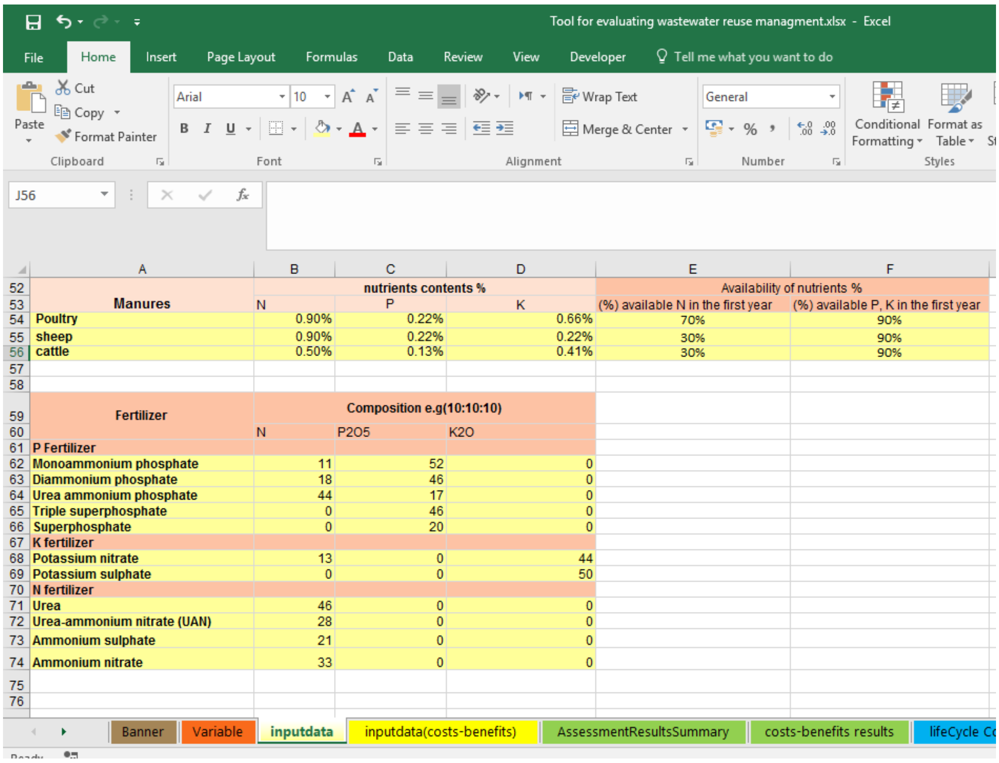
irrigation Water supply		NO3-N+NH4-N mg/l	PO4-P mg/l	K mg/l
		water Quality		
local wells	GW	0	0	0
Man made River supply	MMR	0	0	0
conventional activated sludge	T1	25	7	50
on site(Three-tank system)	T2	45	9	50
on site(Three-tank system +sand Filter)	T3	25	6.5	50
septic tank+ (WSP)	T4	21	6.5	50
treatment plant (WSP)	T5	15	6.5	50
treatment plant (Conventional activated sludge+ disinfection)	T6	25	7	50
Activated sludge+ Biological Nitrogen Removal (MLE)+	T7	8	9	50
Activated sludge+ Ultrfiltration+ reverse osmosis	T8	1	0.5	1
nutrients available from soil				
P kg/h				
K kg/h				
N kg/h				



Tool for evaluating wastewater reuse managment.xlsx - Excel

J56

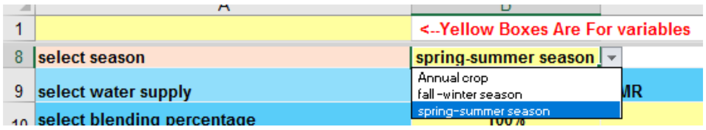
Manures	nutrients contents %			Availability of nutrients %	
	N	P	K	(%) available N in the first year	(%) available P, K in the first year
Poultry	0.90%	0.22%	0.66%	70%	90%
sheep	0.90%	0.22%	0.22%	30%	90%
cattle	0.50%	0.13%	0.41%	30%	90%

Fertilizer	Composition e.g(10:10:10)		
	N	P2O5	K2O
P Fertilizer			
Monoammonium phosphate	11	52	0
Diammonium phosphate	18	46	0
Urea ammonium phosphate	44	17	0
Triple superphosphate	0	46	0
Superphosphate	0	20	0
K fertilizer			
Potassium nitrate	13	0	44
Potassium sulphate	0	0	50
N fertilizer			
Urea	46	0	0
Urea-ammonium nitrate (UAN)	28	0	0
Ammonium sulphate	21	0	0
Ammonium nitrate	33	0	0

Variable

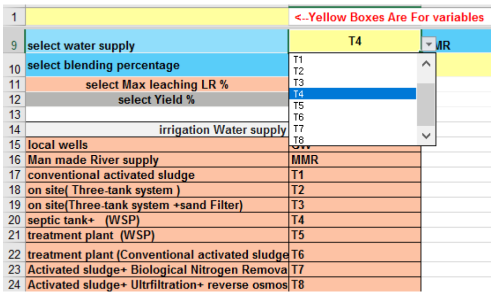
After the entering all required data input, variable worksheet allows the user to compere different management strategies. In this worksheet, the user will be able to select:

Season



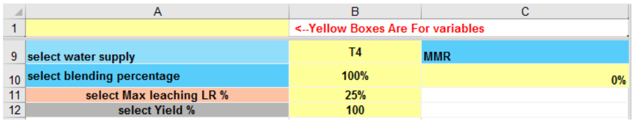
	A	B
1		<--Yellow Boxes Are For variables
8	select season	spring-summer season
9	select water supply	
10	select blending percentage	

Water irrigation supply



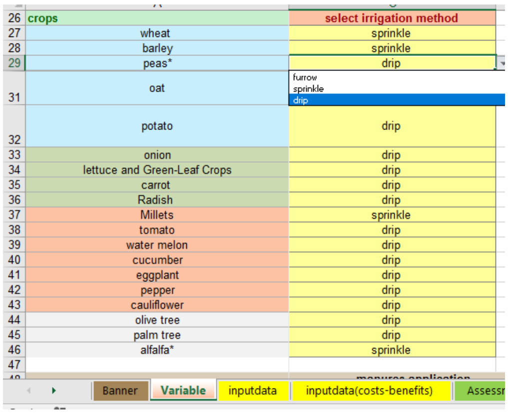
1		<--Yellow Boxes Are For variables
9	select water supply	T4
10	select blending percentage	
11	select Max leaching LR %	
12	select Yield %	
13		
14	irrigation Water supply	
15	local wells	
16	Man made River supply	MMR
17	conventional activated sludge	T1
18	on site(Three-tank system)	T2
19	on site(Three-tank system +sand Filter)	T3
20	septic tank+ (WSP)	T4
21	treatment plant (WSP)	T5
22	treatment plant (Conventional activated sludge	T6
23	Activated sludge+ Biological Nitrogen Remova	T7
24	Activated sludge+ Ultrfiltration+ reverse osmos	T8

Maximum leaching requirement, total yield %, and blending percentage



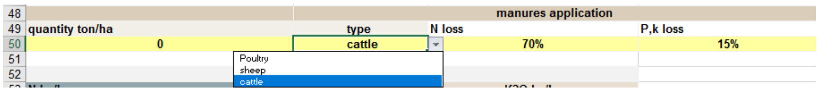
	A	B	C
1		<--Yellow Boxes Are For variables	
9	select water supply	T4	MMR
10	select blending percentage	100%	0%
11	select Max leaching LR %	25%	
12	select Yield %	100	

Irrigation method

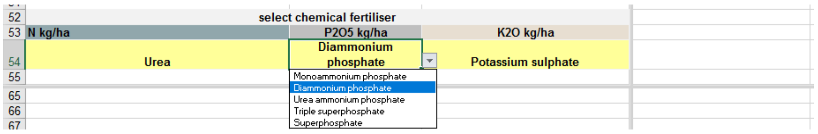


26	crops	select irrigation method
27	wheat	sprinkle
28	barley	sprinkle
29	peas*	drip
31	oat	
32	potato	drip
33	onion	drip
34	lettuce and Green-Leaf Crops	drip
35	carrot	drip
36	Radish	drip
37	Millets	sprinkle
38	tomato	drip
39	water melon	drip
40	cucumber	drip
41	eggplant	drip
42	pepper	drip
43	cauliflower	drip
44	olive tree	drip
45	palm tree	drip
46	alfalfa*	sprinkle
47		

Manure and chemical fertiliser



48		manures application		
49	quantity ton/ha	type	N loss	P,k loss
50	0	cattle	70%	15%
51				
52				

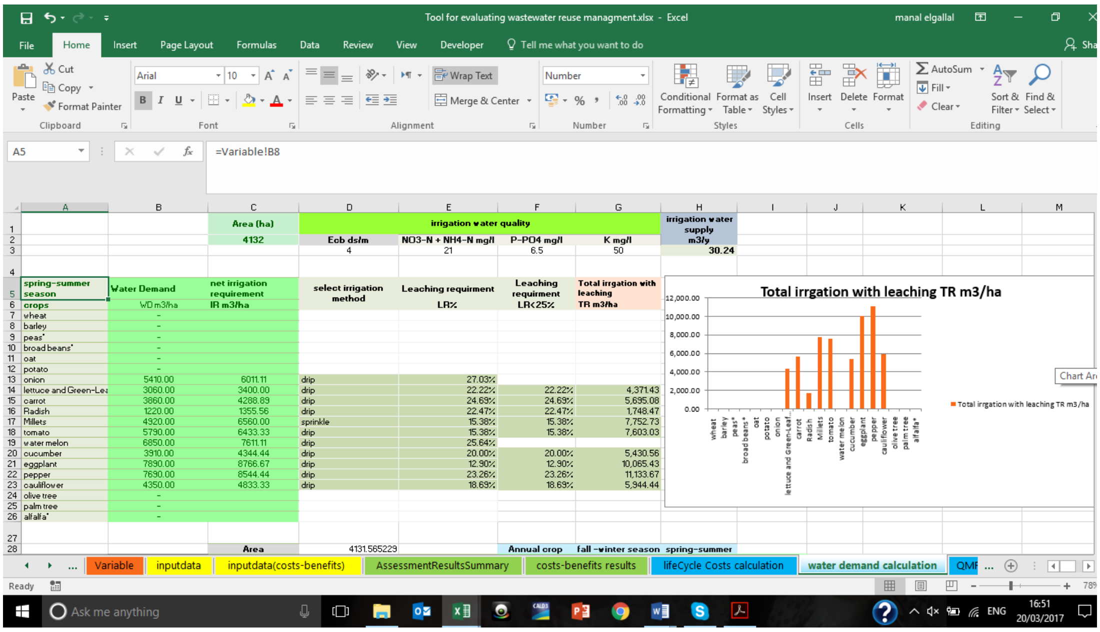


52	select chemical fertiliser		
53	N kg/ha	P2O5 kg/ha	K2O kg/ha
54	Urea	Diammonium phosphate	Potassium sulphate
55			
65			
66			
67			

Calculation

Information from **Input Data** sections are used to calculate the relevant values for which are presented in the **Calculations** section. The user can NOT do any editing in these worksheets

In sheet **water demand calculation**. The tool will calculate leaching requirement using the equation 1 or equation 2 (depending on irrigation system). If leaching requirement greater than 0.25. Blending with freshwater, if available, at specific ratios is required to ensure target salinities in the blended water are achieved. otherwise crops which gives leaching requirement ≤ 0.25 will be selected. Then Gross water requirement for selected crops will be calculated.



A5 =Variable!B8

	A	B	C	D	E	F	G	H
1			Area (ha)	irrigation water quality				irrigation water supply m3/y
2			4132	Ecb ds/m	NO3-N + NH4-N mg/l	P-PO4 mg/l	K mg/l	
3				4	21	6.5	50	30.24
4								
5	spring-summer season	Water Demand	net irrigation requirement	select irrigation method	Leaching requirment	Leaching requirment	Total irrgation with leaching	
6	crops	WD m3/ha	IR m3/ha		LR%	LR<25%	TR m3/ha	
7	wheat	-						
8	barley	-						
9	peas*	-						
10	broad beans*	-						
11	oat	-						
12	potato	-						
13	onion	5410.00	6011.11	drip	27.03%			
14	lettuce and Green-Lea	3060.00	3400.00	drip	22.22%	22.22%	4,371.43	
15	carrot	3860.00	4288.89	drip	24.69%	24.69%	5,695.08	
16	Radish	1220.00	1355.56	drip	22.47%	22.47%	1,748.47	
17	Millets	4920.00	6560.00	sprinkle	15.38%	15.38%	7,752.73	
18	tomato	5790.00	6433.33	drip	15.38%	15.38%	7,603.03	
19	water melon	6850.00	7611.11	drip	25.64%			
20	cucumber	3910.00	4344.44	drip	20.00%	20.00%	5,430.56	
21	eggplant	7890.00	8766.67	drip	12.90%	12.90%	10,065.43	
22	pepper	7690.00	8544.44	drip	23.26%	23.26%	11,133.67	
23	cauliflower	4350.00	4833.33	drip	18.69%	18.69%	5,944.44	
24	olive tree	-						
25	palm tree	-						
26	alfalfa*	-						
27								
28			Area	4131.565229		Annual crop	fall -winter season	spring-summer

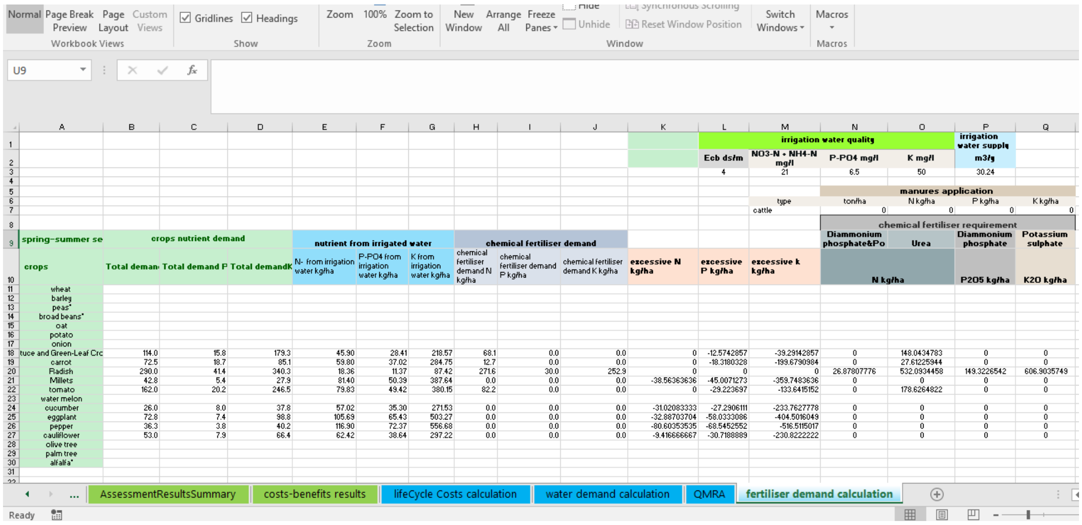
In **fertiliser demand calculation sheet** equation 4 and 5 will be used to Synchronize nutrients (N,P&K) application rates to nutrient demand of selected crops (with leaching requirement ≤ 0.25)

- If(crop nutrient requirment $\left(\frac{\text{kg}}{\text{ha}}\right) <$ nutrients from wastewater $\left(\frac{\text{kg}}{\text{ha}}\right) -$ nutrient available from soil $\left(\frac{\text{kg}}{\text{ha}}\right)$)

  There is excessive nutrient supply. Blending with freshwater, if available, at specific ratios is required. Otherwise select crops with take advantage of high concentration of nutrient.

- If (crop nutrient requirment $\left(\frac{\text{kg}}{\text{ha}}\right) >$ nutrients from wastewater $\left(\frac{\text{kg}}{\text{ha}}\right) -$ nutrient available from soil $\left(\frac{\text{kg}}{\text{ha}}\right)$)

  Additional fertiliser will be required, and equation 6 and 7 used to calculate chemical fertiliser demands



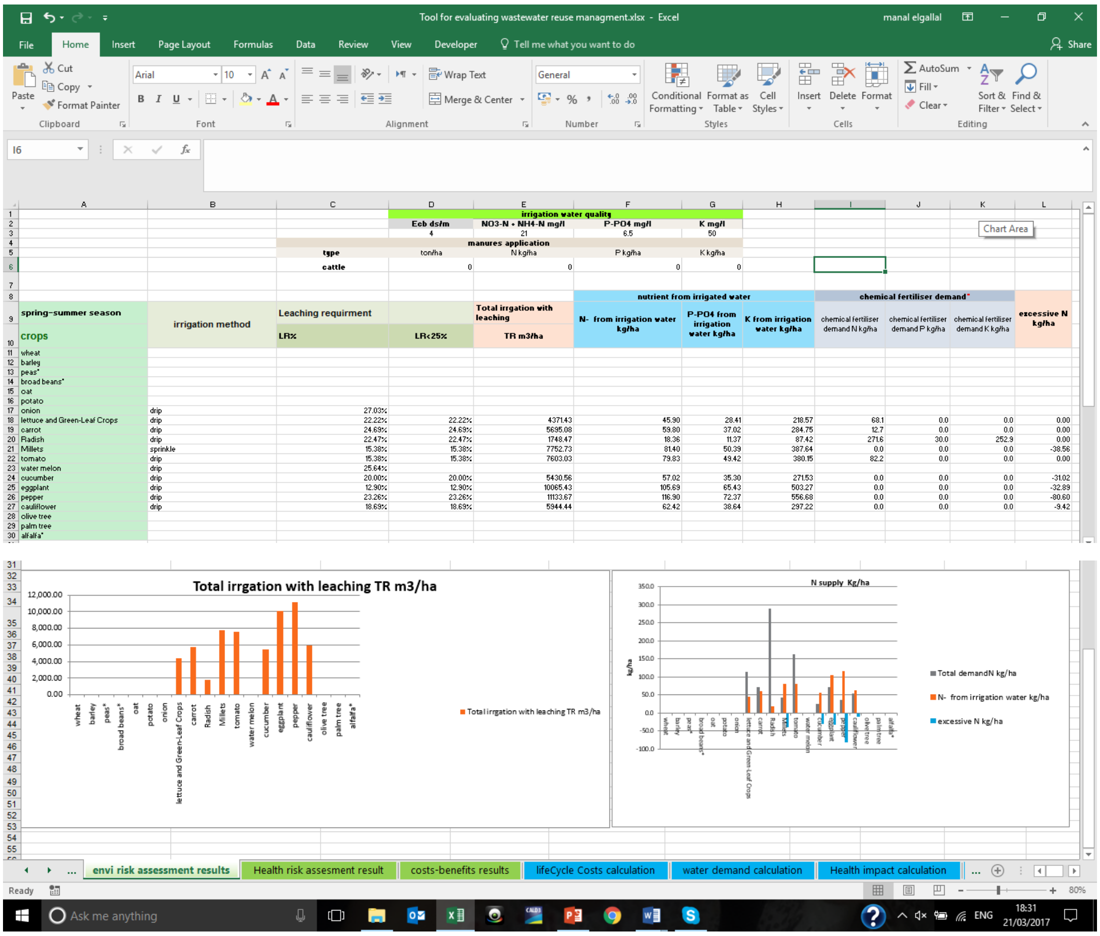
	L	M	N	O	P
1	irrigation water quality				irrigation water supply
2	Ecb ds/m	NO3-N + NH4-N mg/l	P-PO4 mg/l	K mg/l	m3/y
3	4	21	6.5	50	30.24

	M	N	O	P	Q
5		manures application			
6	type	ton/ha	N kg/ha	P kg/ha	K kg/ha
7	cattle	0	0	0	0

spring-summer se	crops nutrient demand			nutrient from irrigated water			chemical fertiliser demand						chemical fertiliser requirement			
													Diammonium phosphate&Po	Urea	Diammonium phosphate	Potassium sulphate
crops	Total deman	Total demand P	Total demandK	N- from irrigation water kg/ha	P-PO4 from irrigation water kg/ha	K from irrigation water kg/ha	chemical fertiliser demand N kg/ha	chemical fertiliser demand P kg/ha	chemical fertiliser demand K kg/ha	excessive N kg/ha	excessive P kg/ha	excessive k kg/ha	N kg/ha		P2O5 kg/ha	K2O kg/ha
wheat																
barley																
peas*																
broad beans*																
oat																
potato																
onion																
tuce and Green-Leaf Crc	114.0	15.8	179.3	45.90	28.41	218.57	68.1	0.0	0.0	0	-12.5742857	-39.29142857	0	148.0434783	0	0
carrot	72.5	18.7	85.1	59.80	37.02	284.75	12.7	0.0	0.0	0	-18.3180328	-199.6790984	0	27.61225944	0	0
Radish	290.0	41.4	340.3	18.36	11.37	87.42	271.6	30.0	252.9	0	0	0	26.87807776	532.0934458	149.3226542	606.9035749
Millets	42.8	5.4	27.9	81.40	50.39	387.64	0.0	0.0	0.0	-38.56363636	-45.0071273	-359.7483636	0	0	0	0
tomato	162.0	20.2	246.5	79.83	49.42	380.15	82.2	0.0	0.0	0	-29.223697	-133.6415152	0	178.6264822	0	0
water melon																
cucumber	26.0	8.0	37.8	57.02	35.30	271.53	0.0	0.0	0.0	-31.02083333	-27.2906111	-233.7627778	0	0	0	0
eggplant	72.8	7.4	98.8	105.69	65.43	503.27	0.0	0.0	0.0	-32.88703704	-58.0333086	-404.5016049	0	0	0	0
pepper	36.3	3.8	40.2	116.90	72.37	556.68	0.0	0.0	0.0	-80.60353535	-68.5452552	-516.5115017	0	0	0	0
cauliflower	53.0	7.9	66.4	62.42	38.64	297.22	0.0	0.0	0.0	-9.416666667	-30.7188889	-230.8222222	0	0	0	0
olive tree																
palm tree																
alfalfa*																

Results

Envi Risk assessment result worksheet, will provide a summary of the results of (crops water requirement, leaching demand, irrigation water quality, nutrient from wastewater, chemical fertiliser demands, and Excessive nitrogen)



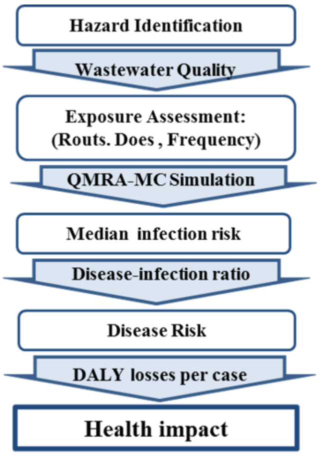
	D	E	F	G
1	irrigation water quality			
2	Ecb ds/m	NO3-N + NH4-N mg/l	P-PO4 mg/l	K mg/l
3	4	21	6.5	50

	C	D	E	F	G
4	manures application				
5	type	ton/ha	N kg/ha	P kg/ha	K kg/ha
6	cattle	0	0	0	0

spring-summer season	irrigation method	Leaching requirment		Total irrgation with leaching	nutrient from irrigated water			chemical fertiliser demand*			excessive N kg/ha
crops		LR%	LR<25%	TR m3/ha	N- from irrigation water kg/ha	P-PO4 from irrigation water kg/ha	K from irrigation water kg/ha	chemical fertiliser demand N kg/ha	chemical fertiliser demand P kg/ha	chemical fertiliser demand K kg/ha	
wheat											
barley											
peas*											
broad beans*											
oat											
potato											
onion	drip	27.03%									
lettuce and Green-Leaf Crops	drip	22.22%	22.22%	4371.43	45.90	28.41	218.57	68.1	0.0	0.0	0.00
carrot	drip	24.69%	24.69%	5695.08	59.80	37.02	284.75	12.7	0.0	0.0	0.00
Radish	drip	22.47%	22.47%	1748.47	18.36	11.37	87.42	271.6	30.0	252.9	0.00
Millets	sprinkle	15.38%	15.38%	7752.73	81.40	50.39	387.64	0.0	0.0	0.0	-38.56
tomato	drip	15.38%	15.38%	7603.03	79.83	49.42	380.15	82.2	0.0	0.0	0.00
water melon	drip	25.64%									
cucumber	drip	20.00%	20.00%	5430.56	57.02	35.30	271.53	0.0	0.0	0.0	-31.02
eggplant	drip	12.90%	12.90%	10065.43	105.69	65.43	503.27	0.0	0.0	0.0	-32.89
pepper	drip	23.26%	23.26%	11133.67	116.90	72.37	556.68	0.0	0.0	0.0	-80.60
cauliflower	drip	18.69%	18.69%	5944.44	62.42	38.64	297.22	0.0	0.0	0.0	-9.42
olive tree											
palm tree											
alfalfa*											

MODEL 2: Health Risk Assessment

Quantitative Microbial Risk Assessment (QMRA) models with 10,000 Monte Carlo simulations (MC-QMRA) based on the improved Karavarsamis-Hamilton method was used to estimate annual median risks of pathogen infections for different wastewater qualities under selected exposure scenarios[8]. Next figure shows the approach by which the results of QMRA are incorporated in the tool to estimate health impacts associated with alternative wastewater reuse strategies in terms of DALYs were estimated.

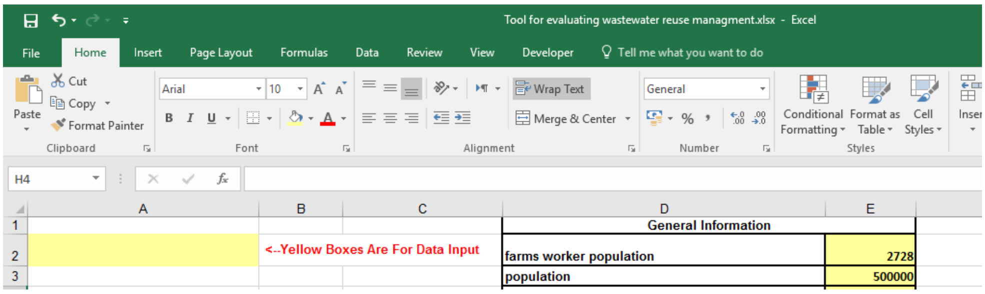


Health Risk Assessment

Data input

Data input includes: the results of QMRA-MC Simulation (as annual median risks), population, farms worker population (total number of farmer worker and families) (**fill the yellow calls**)

In Data Input Sheet This is what you see for estimating health impact health impacts associated with alternative wastewater reuse strategies in terms of DALYs were estimated



	A	B	C	D	E
1				General Information	
2		<--Yellow Boxes Are For Data Input		farms worker population	2728
3				population	500000

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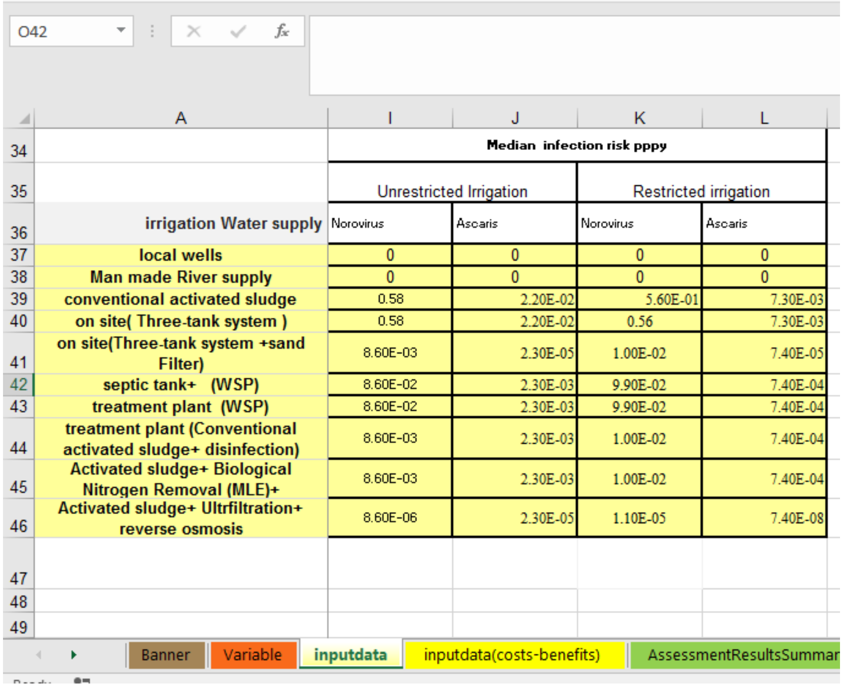
[8] Simulations using QMRA: A Beginners Guide - Monte carlo simulation programmes, available at (the program is available at: http://www.personal.leeds.ac.uk/~cen6ddm/QMRAbeginners.html)

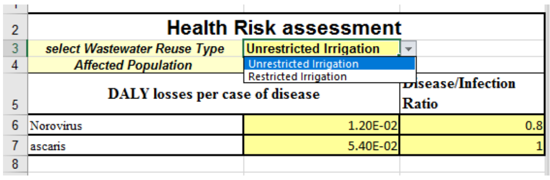


	Median infection risk pppy			
	Unrestricted Irrigation		Restricted irrigation	
irrigation Water supply	Norovirus	Ascaris	Norovirus	Ascaris
local wells	0	0	0	0
Man made River supply	0	0	0	0
conventional activated sludge	0.58	2.20E-02	5.60E-01	7.30E-03
on site(Three-tank system)	0.58	2.20E-02	0.56	7.30E-03
on site(Three-tank system +sand Filter)	8.60E-03	2.30E-05	1.00E-02	7.40E-05
septic tank+ (WSP)	8.60E-02	2.30E-03	9.90E-02	7.40E-04
treatment plant (WSP)	8.60E-02	2.30E-03	9.90E-02	7.40E-04
treatment plant (Conventional activated sludge+ disinfection)	8.60E-03	2.30E-03	1.00E-02	7.40E-04
Activated sludge+ Biological Nitrogen Removal (MLE)+	8.60E-03	2.30E-03	1.00E-02	7.40E-04
Activated sludge+ Ultrfiltration+ reverse osmosis	8.60E-06	2.30E-05	1.10E-05	7.40E-08

Variable

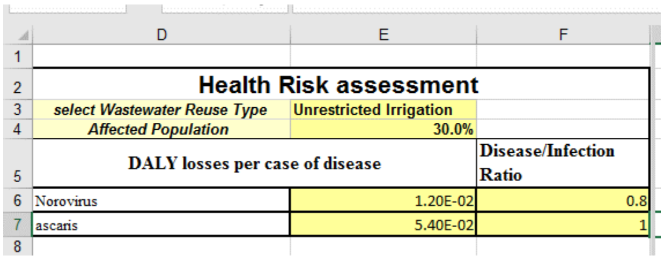
From variable worksheet, the user will choose:

- **Wastewater reuse type:**



Health Risk assessment		
select Wastewater Reuse Type	Unrestricted Irrigation	
Affected Population		
DALY losses per case of disease		Disease/Infection Ratio
Norovirus	1.20E-02	0.8
ascaris	5.40E-02	1

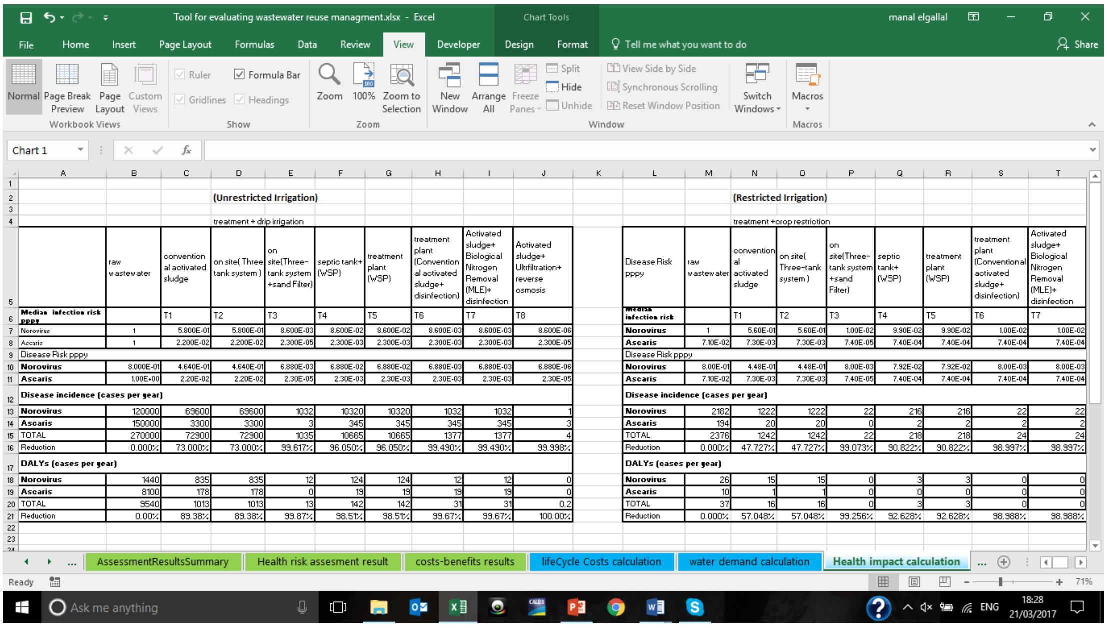
- **Affected population portion (In the case of unrestricted irrigation)**
- **DALY losses per case of disease**
- **Disease /infection ratio**



Health Risk assessment		
select Wastewater Reuse Type	Unrestricted Irrigation	
Affected Population	30.0%	
DALY losses per case of disease		Disease/Infection Ratio
Norovirus	1.20E-02	0.8
ascaris	5.40E-02	1

Calculation

information from input data (**QMRA results)** sections are used to calculate the health impact as a result of consuming wastewater irrigated crops (unrestricted irrigation) and the impact on farmer's health (restricted irrigation) as a result of exposure to wastewater effluent from different treatment options. the relevant values are presented in the health impact calculation sheet. The user can NOT do any editing in these worksheet



(Unrestricted Irrigation)

treatment + drip irrigation

	raw wastewater	conventional activated sludge	on site(Three tank system)	on site(Three-tank system +sand Filter)	septic tank+ (WSP)	treatment plant (WSP)	treatment plant (Conventional activated sludge+ disinfection)	Activated sludge+ Biological Nitrogen Removal (MLE)+ disinfection	Activated sludge+ Ultrfiltration+ reverse osmosis
Median infection risk pppy		T1	T2	T3	T4	T5	T6	T7	T8
Norovirus	1	5.800E-01	5.800E-01	8.600E-03	8.600E-02	8.600E-02	8.600E-03	8.600E-03	8.600E-06
Ascaris	1	2.200E-02	2.200E-02	2.300E-05	2.300E-03	2.300E-03	2.300E-03	2.300E-03	2.300E-05
Disease Risk pppy									
Norovirus	8.000E-01	4.640E-01	4.640E-01	6.880E-03	6.880E-02	6.880E-02	6.880E-03	6.880E-03	6.880E-06
Ascaris	1.00E+00	2.20E-02	2.20E-02	2.30E-05	2.30E-03	2.30E-03	2.30E-03	2.30E-03	2.30E-05
Disease incidence (cases per year)									
Norovirus	120000	69600	69600	1032	10320	10320	1032	1032	1
Ascaris	150000	3300	3300	3	345	345	345	345	3
TOTAL	270000	72900	72900	1035	10665	10665	1377	1377	4
Reduction	0.000%	73.000%	73.000%	99.617%	96.050%	96.050%	99.490%	99.490%	99.998%
DALYs (cases per year)									
Norovirus	1440	835	835	12	124	124	12	12	0
Ascaris	8100	178	178	0	19	19	19	19	0
TOTAL	9540	1013	1013	13	142	142	31	31	0.2
Reduction	0.00%	89.38%	89.38%	99.87%	98.51%	98.51%	99.67%	99.67%	100.00%

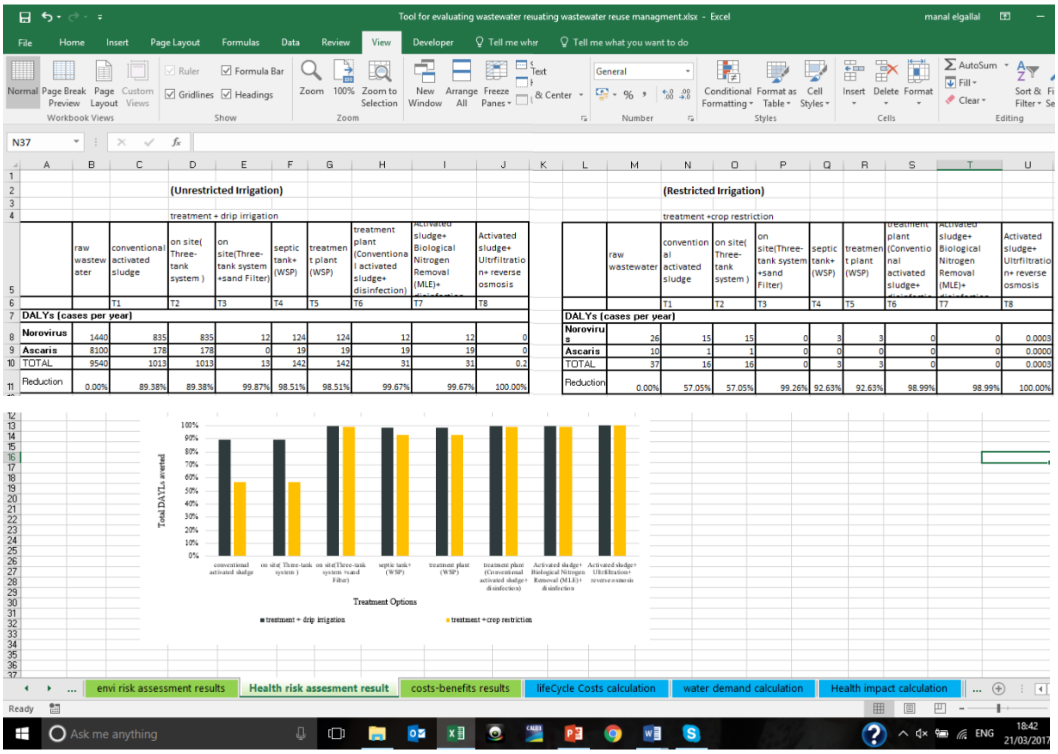
(Restricted Irrigation)

treatment +crop restriction

Disease Risk pppy	raw wastewater	conventional activated sludge	on site(Three-tank system)	on site(Three-tank system +sand Filter)	septic tank+ (WSP)	treatment plant (WSP)	treatment plant (Conventional activated sludge+ disinfection)	Activated sludge+ Biological Nitrogen Removal (MLE)+ disinfection
Median infection risk		T1	T2	T3	T4	T5	T6	T7
Norovirus	1	5.60E-01	5.60E-01	1.00E-02	9.90E-02	9.90E-02	1.00E-02	1.00E-02
Ascaris	7.10E-02	7.30E-03	7.30E-03	7.40E-05	7.40E-04	7.40E-04	7.40E-04	7.40E-04
Disease Risk pppy								
Norovirus	8.00E-01	4.48E-01	4.48E-01	8.00E-03	7.92E-02	7.92E-02	8.00E-03	8.00E-03
Ascaris	7.10E-02	7.30E-03	7.30E-03	7.40E-05	7.40E-04	7.40E-04	7.40E-04	7.40E-04
Disease incidence (cases per year)								
Norovirus	2182	1222	1222	22	216	216	22	22
Ascaris	194	20	20	0	2	2	2	2
TOTAL	2376	1242	1242	22	218	218	24	24
Reduction	0.000%	47.727%	47.727%	99.073%	90.822%	90.822%	98.997%	98.997%
DALYs (cases per year)								
Norovirus	26	15	15	0	3	3	0	0
Ascaris	10	1	1	0	0	0	0	0
TOTAL	37	16	16	0	3	3	0	0
Reduction	0.000%	57.048%	57.048%	99.256%	92.628%	92.628%	98.988%	98.988%

Results

Health risk assessment worksheet, summarise the result of health impact from both restricted and unrestricted irrigation as result of wastewater reuse in agriculture in term of DALYs (cases per year) and total DALYS Adverted by different reuse strategies.



(Unrestricted Irrigation)

treatment + drip irrigation

	raw wastewater	conventional activated sludge	on site(Three-tank system)	on site(Three-tank system +sand Filter)	septic tank+ (WSP)	treatment plant (WSP)	treatment plant (Conventional activated sludge+ disinfection)	Activated sludge+ Biological Nitrogen Removal (MLE)+	Activated sludge+ Ultrfiltration+ reverse osmosis
		T1	T2	T3	T4	T5	T6	T7	T8
DALYs (cases per year)									
Norovirus	1440	835	835	12	124	124	12	12	0
Ascaris	8100	178	178	0	19	19	19	19	0
TOTAL	9540	1013	1013	13	142	142	31	31	0.2
Reduction	0.00%	89.38%	89.38%	99.87%	98.51%	98.51%	99.67%	99.67%	100.00%

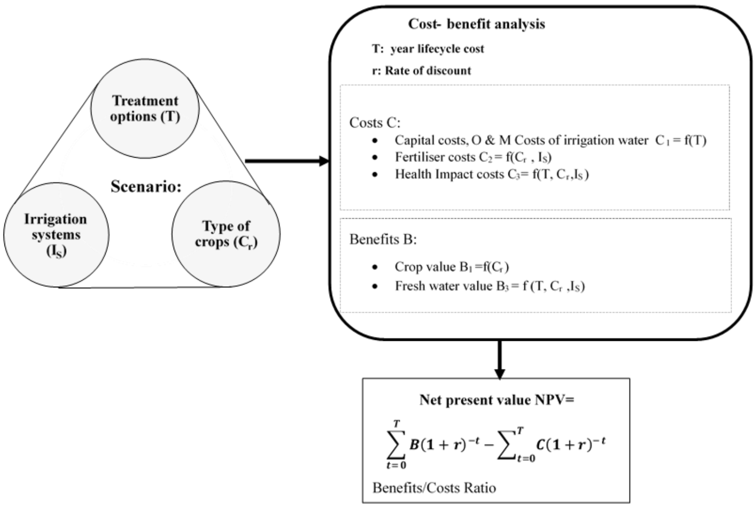
(Restricted Irrigation)

treatment +crop restriction

	raw wastewater	conventional activated sludge	on site(Three-tank system)	on site(Three-tank system +sand Filter)	septic tank+ (WSP)	treatment plant (WSP)	treatment plant (Conventional activated sludge+	Activated sludge+ Biological Nitrogen Removal (MLE)+	Activated sludge+ Ultrfiltration+ reverse osmosis
		T1	T2	T3	T4	T5	T6	T7	T8
DALYs (cases per year)									
Norovirus	26	15	15	0	3	3	0	0	0.0003
Ascaris	10	1	1	0	0	0	0	0	0.0000
TOTAL	37	16	16	0	3	3	0	0	0.0003
Reduction	0.00%	57.05%	57.05%	99.26%	92.63%	92.63%	98.99%	98.99%	100.00%

MODEL 3: Costs and Benefits Analysis (CBA)

Cost benefit analysis was used to evaluate the *economic efficiency* of those risk management strategies for reusing wastewater in agriculture which had already been shown to have the best outcomes in terms of health and environment. Thus, cost benefit analysis is the final step to identify optimum strategies for the reuse of wastewater in agricultural irrigation. Next figure provides the analytical framework for the CBA



Analytical framework of Costs- benefits analysis

Data input

1. Costs Estimation

Three cost components were included in the calculations: capital, operational and maintenance (O&M) costs of infrastructure; fertiliser costs; and the value of of negative health Impacts.

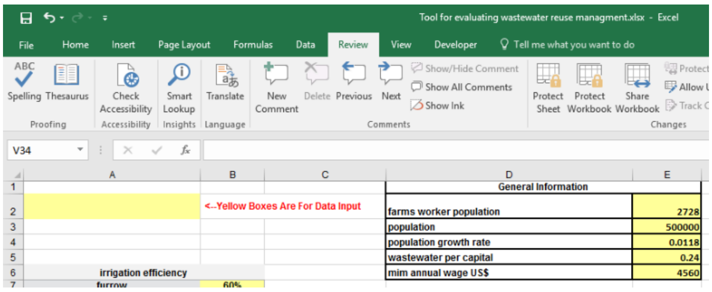
Fertiliser costs = $\sum \boldsymbol{Chemical\ fertliser\ demands} \left(\frac{\boldsymbol{ton}}{\boldsymbol{ha}}\right) \times$
$\boldsymbol{A}(\boldsymbol{ha})\ \boldsymbol{fertiliser\ price}\ \left(\frac{\boldsymbol{US\$}}{\boldsymbol{ton}}\right)$ Equation 8

the value of of negative health Impacts= Total DALY loss x Annual Wage Equation 9

Data input for costs estimation includes:

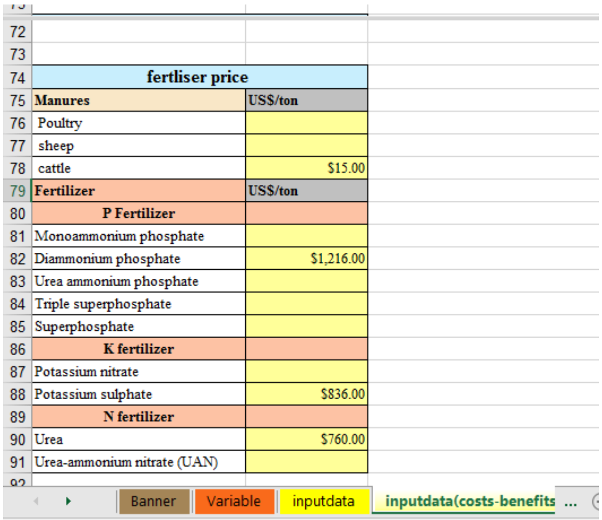
Data input for costs estimation includes:

- General information needed for life cycle costs (such as population, wastewater consumption per capital and population growth rate and min annual wage). **In Data Input Sheet this is what you see (fill the yellow calls)**



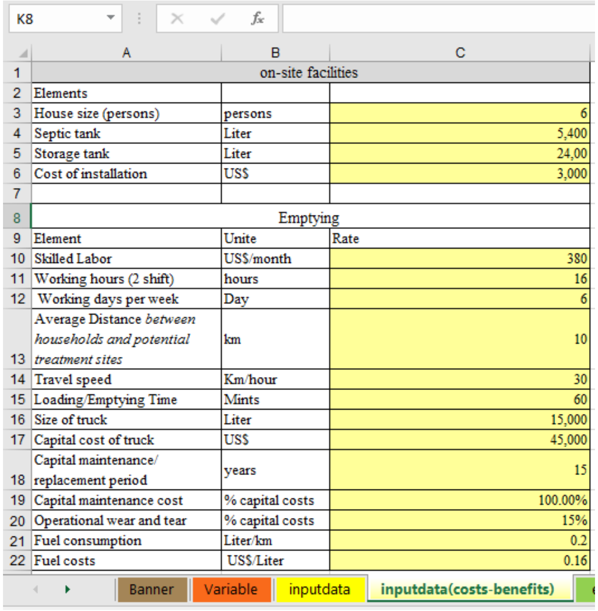
	A	B	C	D	E
1				General Information	
2		<--Yellow Boxes Are For Data Input		farms worker population	2728
3				population	500000
4				population growth rate	0.0118
5				wastewater per capital	0.24
6	irrigation efficiency			mim annual wage US$	4560
7	furrow	60%			

- Price of fertliser. In Data Input (cost-benefits) **Sheet this is what you see** (**fill the yellow calls**)

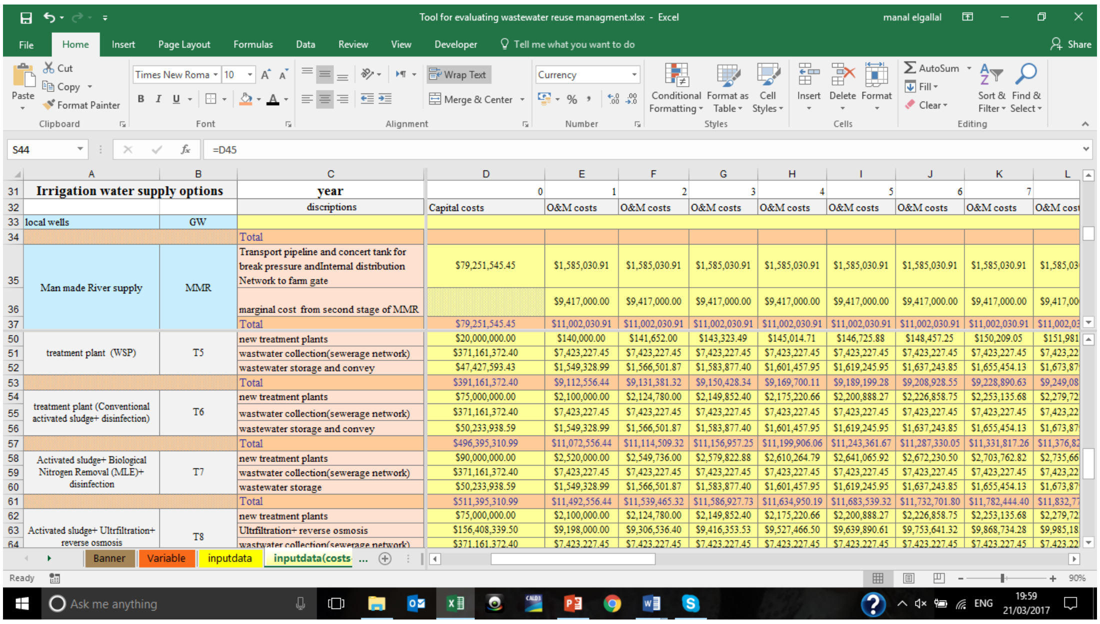


72		
73		
74	**fertliser price**	
75	**Manures**	**US$/ton**
76	Poultry	
77	sheep	
78	cattle	$15.00
79	**Fertilizer**	**US$/ton**
80	**P Fertilizer**	
81	Monoammonium phosphate	
82	Diammonium phosphate	$1,216.00
83	Urea ammonium phosphate	
84	Triple superphosphate	
85	Superphosphate	
86	**K fertilizer**	
87	Potassium nitrate	
88	Potassium sulphate	$836.00
89	**N fertilizer**	
90	Urea	$760.00
91	Urea-ammonium nitrate (UAN)	

- Capital, Operational and Maintenance (O&M) costs of infrastructure. **In** Data Input (cost-benefit) **Sheet this is what you see (fill the yellow calls)**



	A	B	C
1	on-site facilities		
2	Elements		
3	House size (persons)	persons	6
4	Septic tank	Liter	5,400
5	Storage tank	Liter	24,00
6	Cost of installation	US$	3,000
7			
8	Emptying		
9	Element	Unite	Rate
10	Skilled Labor	US$/month	380
11	Working hours (2 shift)	hours	16
12	Working days per week	Day	6
13	Average Distance *between households and potential treatment sites*	km	10
14	Travel speed	Km/hour	30
15	Loading/Emptying Time	Mints	60
16	Size of truck	Liter	15,000
17	Capital cost of truck	US$	45,000
18	Capital maintenance/ replacement period	years	15
19	Capital maintenance cost	% capital costs	100.00%
20	Operational wear and tear	% capital costs	15%
21	Fuel consumption	Liter/km	0.2
22	Fuel costs	US$/Liter	0.16



S44 =D45

	A	B	C	D	E	F	G	H	I	J	K	L
31	**Irrigation water supply options**		**year**	0	1	2	3	4	5	6	7	
32			discriptions	Capital costs	O&M costs	O&M costs	O&M costs	O&M costs	O&M costs	O&M costs	O&M costs	O&M cost
33	local wells	GW										
34			Total									
35	Man made River supply	MMR	Transport pipeline and concert tank for break pressure andInternal distribution Network to farm gate	$79,251,545.45	$1,585,030.91	$1,585,030.91	$1,585,030.91	$1,585,030.91	$1,585,030.91	$1,585,030.91	$1,585,030.91	$1,585,03
36			marginal cost from second stage of MMR		$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,00
37			Total	$79,251,545.45	$11,002,030.91	$11,002,030.91	$11,002,030.91	$11,002,030.91	$11,002,030.91	$11,002,030.91	$11,002,030.91	$11,002,03
50	treatment plant (WSP)	T5	new treatment plants	$20,000,000.00	$140,000.00	$141,652.00	$143,323.49	$145,014.71	$146,725.88	$148,457.25	$150,209.05	$151,981
51			wastwater collection(sewerage network)	$371,161,372.40	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,22
52			wastewater storage and convey	$47,427,593.43	$1,549,328.99	$1,566,501.87	$1,583,877.40	$1,601,457.95	$1,619,245.95	$1,637,243.85	$1,655,454.13	$1,673,87
53			Total	$391,161,372.40	$9,112,556.44	$9,131,381.32	$9,150,428.34	$9,169,700.11	$9,189,199.28	$9,208,928.55	$9,228,890.63	$9,249,08
54	treatment plant (Conventional activated sludge+ disinfection)	T6	new treatment plants	$75,000,000.00	$2,100,000.00	$2,124,780.00	$2,149,852.40	$2,175,220.66	$2,200,888.27	$2,226,858.75	$2,253,135.68	$2,279,72
55			wastwater collection(sewerage network)	$371,161,372.40	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,22
56			wastewater storage and convey	$50,233,938.59	$1,549,328.99	$1,566,501.87	$1,583,877.40	$1,601,457.95	$1,619,245.95	$1,637,243.85	$1,655,454.13	$1,673,87
57			Total	$496,395,310.99	$11,072,556.44	$11,114,509.32	$11,156,957.25	$11,199,906.06	$11,243,361.67	$11,287,330.05	$11,331,817.26	$11,376,82
58	Activated sludge+ Biological Nitrogen Removal (MLE)+ disinfection	T7	new treatment plants	$90,000,000.00	$2,520,000.00	$2,549,736.00	$2,579,822.88	$2,610,264.79	$2,641,065.92	$2,672,230.50	$2,703,762.82	$2,735,66
59			wastwater collection(sewerage network)	$371,161,372.40	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,22
60			wastewater storage	$50,233,938.59	$1,549,328.99	$1,566,501.87	$1,583,877.40	$1,601,457.95	$1,619,245.95	$1,637,243.85	$1,655,454.13	$1,673,87
61			Total	$511,395,310.99	$11,492,556.44	$11,539,465.32	$11,586,927.73	$11,634,950.19	$11,683,539.32	$11,732,701.80	$11,782,444.40	$11,832,77
62	Activated sludge+ Ultrfiltration+ reverse osmosis	T8	new treatment plants	$75,000,000.00	$2,100,000.00	$2,124,780.00	$2,149,852.40	$2,175,220.66	$2,200,888.27	$2,226,858.75	$2,253,135.68	$2,279,72
63			Ultrfiltration+ reverse osmosis	$156,408,339.50	$9,198,000.00	$9,306,536.40	$9,416,353.53	$9,527,466.50	$9,639,890.61	$9,753,641.32	$9,868,734.28	$9,985,18
64			wastwater collection(sewerage network)	$371,161,372.40	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,227.45	$7,423,22

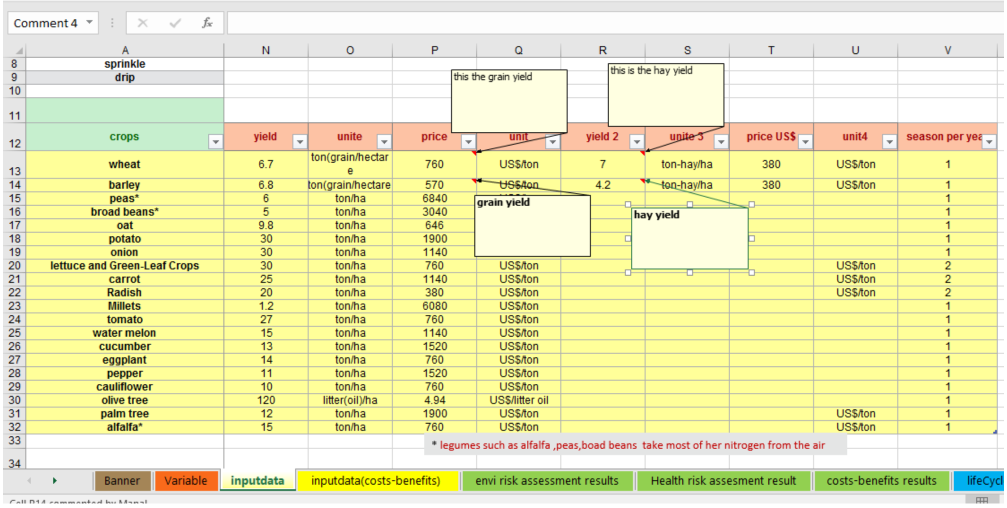
2. Benefits estimation

The benefits were estimated in terms of crop value and fresh water value

- Crops value= $\sum crop\ yeid\ \left(\frac{ton}{ha}\right) \times area(ha)\ \times crop\ price\ \left(\frac{US\$}{ton}\right)$
- The value of fresh water is the value or opportunity cost saved due to water not required from other sources i.e. water being saved or exchanged with other users. In this research, fresh water value was considered as the avoided marginal O&M costs of transport water via man-made river for agricultural supply

Data input for benefits estimation includes:

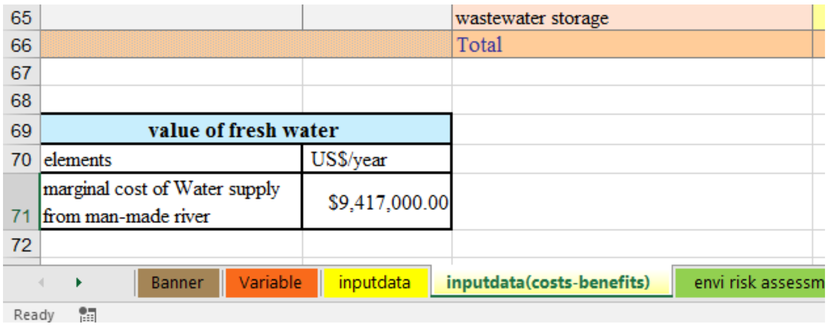
- Crops yield and price**. In Data Input Sheet this is what you see** (**fill the yellow calls**)



	A	N	O	P	Q	R	S	T	U	V
8	sprinkle									
9	drip									
10										
11										
12	crops	yield	unite	price	unit	yield 2	unite 3	price US$	unit4	season per yea
13	wheat	6.7	ton(grain/hectare	760	US$/ton	7	ton-hay/ha	380	US$/ton	1
14	barley	6.8	ton(grain/hectare	570	US$/ton	4.2	ton-hay/ha	380	US$/ton	1
15	peas*	6	ton/ha	6840						1
16	broad beans*	5	ton/ha	3040						1
17	oat	9.8	ton/ha	646						1
18	potato	30	ton/ha	1900						1
19	onion	30	ton/ha	1140						1
20	lettuce and Green-Leaf Crops	30	ton/ha	760	US$/ton				US$/ton	2
21	carrot	25	ton/ha	1140	US$/ton				US$/ton	2
22	Radish	20	ton/ha	380	US$/ton				US$/ton	2
23	Millets	1.2	ton/ha	6080	US$/ton					1
24	tomato	27	ton/ha	760	US$/ton					1
25	water melon	15	ton/ha	1140	US$/ton					1
26	cucumber	13	ton/ha	1520	US$/ton					1
27	eggplant	14	ton/ha	760	US$/ton					1
28	pepper	11	ton/ha	1520	US$/ton					1
29	cauliflower	10	ton/ha	760	US$/ton					1
30	olive tree	120	litter(oil)/ha	4.94	US$/litter oil					1
31	palm tree	12	ton/ha	1900	US$/ton				US$/ton	1
32	alfalfa*	15	ton/ha	760	US$/ton				US$/ton	1
33										
34										

* legumes such as alfalfa ,peas,boad beans take most of her nitrogen from the air

- Freash water value. **In Data Input (cost-benefit) Sheet this is what you see (fill the yellow calls)**

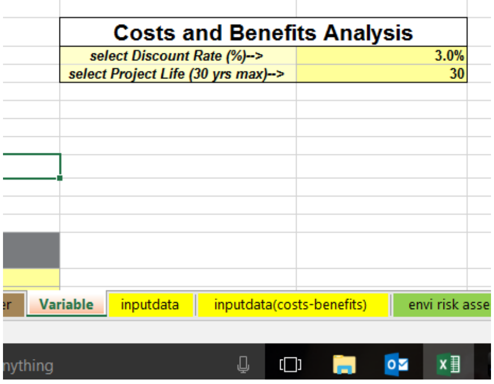


65			wastewater storage
66			Total
67			
68			
69	value of fresh water		
70	elements	US$/year	
71	marginal cost of Water supply from man-made river	$9,417,000.00	
72			

Variable

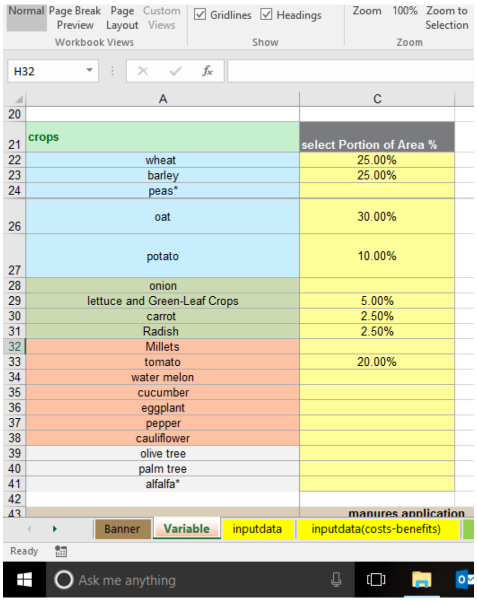
From variable worksheet, the user will select:

- **Discount Rate (%)**
- **Project lifecycle**



Costs and Benefits Analysis	
select Discount Rate (%)-->	3.0%
select Project Life (30 yrs max)-->	30

- **crops pattern and land use**

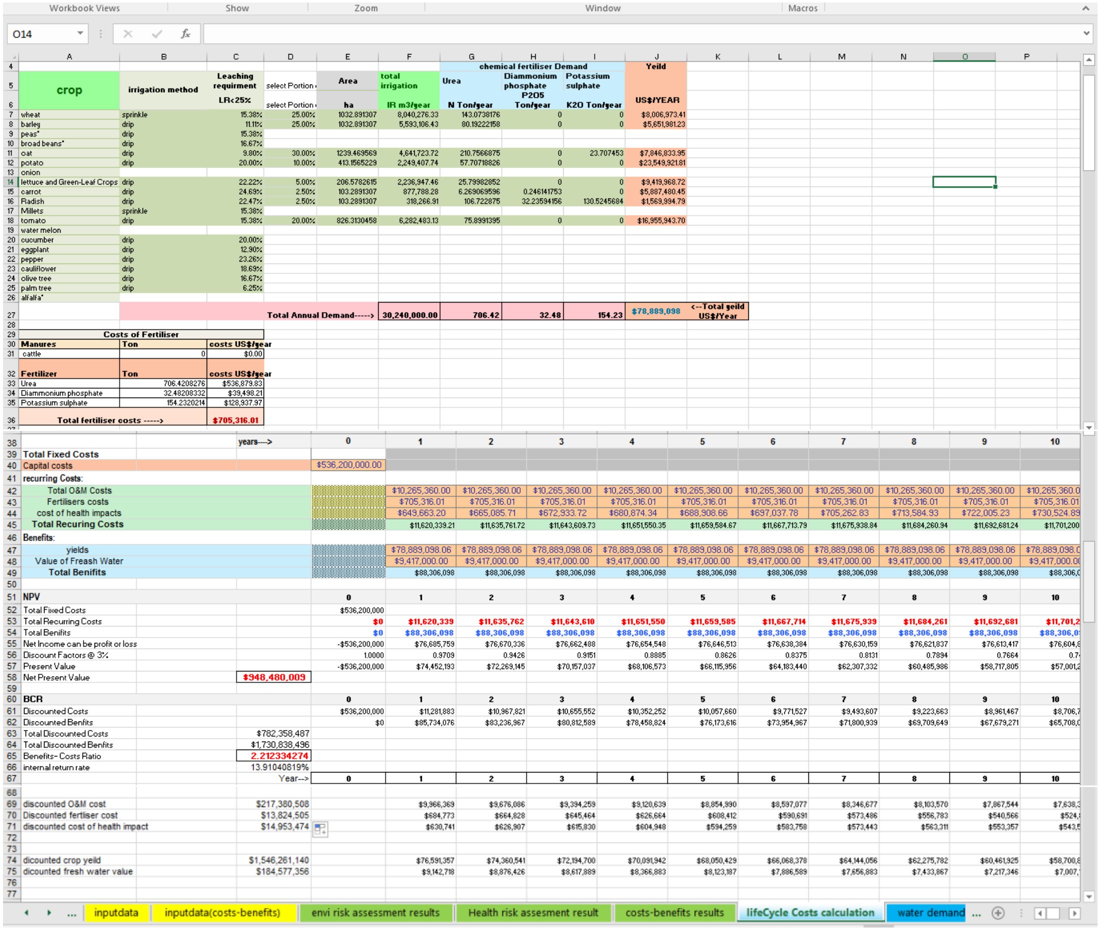


	A	C
20		
21	crops	select Portion of Area %
22	wheat	25.00%
23	barley	25.00%
24	peas*	
26	oat	30.00%
27	potato	10.00%
28	onion	
29	lettuce and Green-Leaf Crops	5.00%
30	carrot	2.50%
31	Radish	2.50%
32	Millets	
33	tomato	20.00%
34	water melon	
35	cucumber	
36	eggplant	
37	pepper	
38	cauliflower	
39	olive tree	
40	palm tree	
41	alfalfa*	
42		
43		manures application

Calculation

Information from **Input Data** sections are used to calculate the present value of costs (including capital costs, O&M costs, fertiliser costs and costs of health impact); the present value of benefits (including the crops yield and fresh water value); net present value NPV, benefit costs (B/C) ratio, and Internal rate of return IRR of alternative wastewater reuse options for which are presented in the **lifecycle costs calculation** section

For each option, a cost function was constructed which comprised initial capital costs incurred in initial years plus an annual operation and maintenance budget incurred in each year of an assumed 30-year lifecycle. These costs were then summed and discounted to give a total project present value of costs; similarly, all annual benefits were summed and discounted to give a total project present value of benefits. Then the total present value of costs and benefits presented are used to calculate the net present value NPV, B/C ratio, and IRR are for each option. The user can NOT do any editing in these worksheet



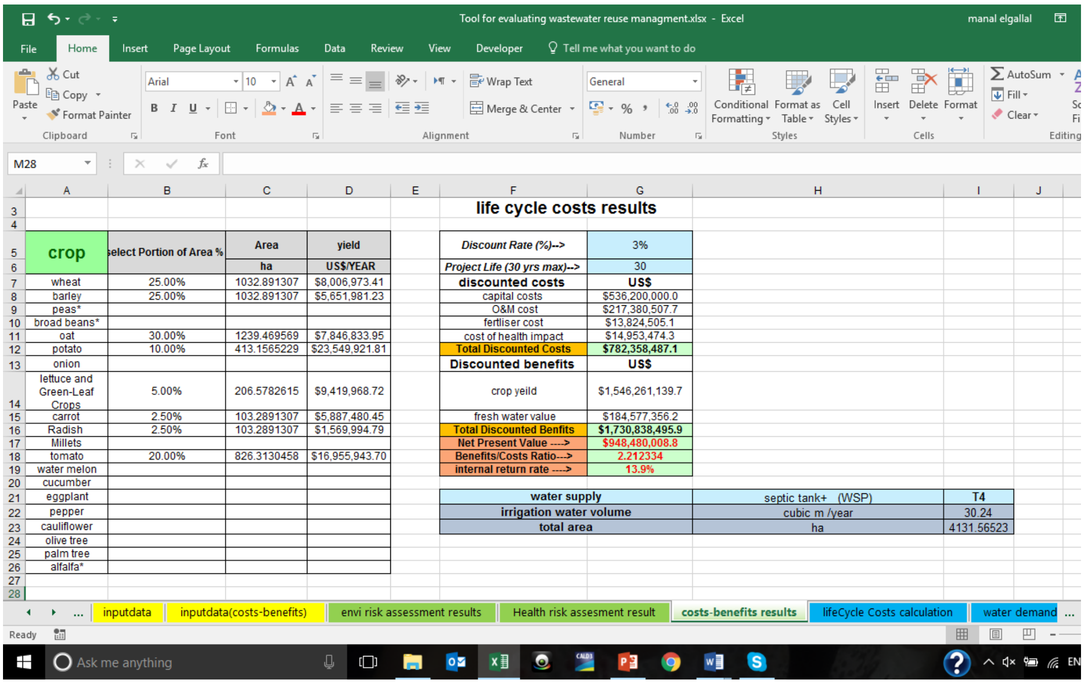
	A	B	C	D	E	F	G	H	I	J	K
4							chemical fertiliser Demand			Yeild	
5	crop	irrigation method	Leaching requirment	select Portion	Area	total irrigation	Urea	Diammonium phosphate	Potassium sulphate		
6			LR<25%	select Portion	ha	IR m3/year	N Ton/year	P2O5 Ton/year	K2O Ton/year	US$/YEAR	
7	wheat	sprinkle	15.38%	25.00%	1032.891307	8,040,276.33	143.0738176	0	0	$8,006,973.41	
8	barley	drip	11.11%	25.00%	1032.891307	5,593,106.43	80.19222158	0	0	$5,651,981.23	
9	peas*	drip	15.38%								
10	broad beans*	drip	16.67%								
11	oat	drip	9.80%	30.00%	1239.469569	4,641,723.72	210.7566875	0	23.707453	$7,846,833.95	
12	potato	drip	20.00%	10.00%	413.1565229	2,249,407.74	57.70718826	0	0	$23,549,921.81	
13	onion										
14	lettuce and Green-Leaf Crops	drip	22.22%	5.00%	206.5782615	2,236,947.46	25.79982852	0	0	$9,419,968.72	
15	carrot	drip	24.69%	2.50%	103.2891307	877,788.28	6.269069596	0.246141753	0	$5,887,480.45	
16	Radish	drip	22.47%	2.50%	103.2891307	318,266.91	106.722875	32.23594156	130.5245684	$1,569,994.79	
17	Millets	sprinkle	15.38%								
18	tomato	drip	15.38%	20.00%	826.3130458	6,282,483.13	75.8991395	0	0	$16,955,943.70	
19	water melon										
20	cucumber	drip	20.00%								
21	eggplant	drip	12.90%								
22	pepper	drip	23.26%								
23	cauliflower	drip	18.69%								
24	olive tree	drip	16.67%								
25	palm tree	drip	6.25%								
26	alfalfa*										
27					Total Annual Demand----->	30,240,000.00	706.42	32.48	154.23	$78,889,098	<--Total yeild US$/Year

	A	B	C
29	Costs of Fertiliser		
30	Manures	Ton	costs US$/year
31	cattle	0	$0.00
32	Fertilizer	Ton	costs US$/year
33	Urea	706.4208276	$536,879.83
34	Diammonium phosphate	32.48208332	$39,498.21
35	Potassium sulphate	154.2320214	$128,937.97
36	Total fertiliser costs ----->		$705,316.01

			0	1	2	3	4	5	6	7	8	9	10
38		years--->	0	1	2	3	4	5	6	7	8	9	10
39	Total Fixed Costs												
40	Capital costs		$536,200,000.00										
41	recurring Costs:												
42	Total O&M Costs			$10,265,360.00	$10,265,360.00	$10,265,360.00	$10,265,360.00	$10,265,360.00	$10,265,360.00	$10,265,360.00	$10,265,360.00	$10,265,360.00	$10,265,360.0
43	Fertilisers costs			$705,316.01	$705,316.01	$705,316.01	$705,316.01	$705,316.01	$705,316.01	$705,316.01	$705,316.01	$705,316.01	$705,316.01
44	cost of health impacts			$649,663.20	$665,085.71	$672,933.72	$680,874.34	$688,908.66	$697,037.78	$705,262.83	$713,584.93	$722,005.23	$730,524.89
45	Total Recuring Costs			$11,620,339.21	$11,635,761.72	$11,643,609.73	$11,651,550.35	$11,659,584.67	$11,667,713.79	$11,675,938.84	$11,684,260.94	$11,692,681.24	$11,701,200
46	Benefits:												
47	yields			$78,889,098.06	$78,889,098.06	$78,889,098.06	$78,889,098.06	$78,889,098.06	$78,889,098.06	$78,889,098.06	$78,889,098.06	$78,889,098.06	$78,889,098.0
48	Value of Freash Water			$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.00	$9,417,000.0
49	Total Benifits			$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,0
51	NPV		0	1	2	3	4	5	6	7	8	9	10
52	Total Fixed Costs		$536,200,000										
53	Total Recurring Costs		$0	$11,620,339	$11,635,762	$11,643,610	$11,651,550	$11,659,585	$11,667,714	$11,675,939	$11,684,261	$11,692,681	$11,701,2
54	Total Benifits		$0	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,098	$88,306,0
55	Net Income can be profit or loss		-$536,200,000	$76,685,759	$76,670,336	$76,662,488	$76,654,548	$76,646,513	$76,638,384	$76,630,159	$76,621,837	$76,613,417	$76,604,8
56	Discount Factors @ 3%		1.0000	0.9709	0.9426	0.9151	0.8885	0.8626	0.8375	0.8131	0.7894	0.7664	0.7
57	Present Value		-$536,200,000	$74,452,193	$72,269,145	$70,157,037	$68,106,573	$66,115,956	$64,183,440	$62,307,332	$60,485,986	$58,717,805	$57,001,2
58	Net Present Value	$948,480,009											
60	BCR		0	1	2	3	4	5	6	7	8	9	10
61	Discounted Costs		$536,200,000	$11,281,883	$10,967,821	$10,655,552	$10,352,252	$10,057,660	$9,771,527	$9,493,607	$9,223,663	$8,961,467	$8,706,7
62	Discounted Benfits		$0	$85,734,076	$83,236,967	$80,812,589	$78,458,824	$76,173,616	$73,954,967	$71,800,939	$69,709,649	$67,679,271	$65,708,0
63	Total Discounted Costs	$782,358,487											
64	Total Discounted Benfits	$1,730,838,496											
65	Benefits- Costs Ratio	2.212334274											
66	internal return rate	13.91040819%											
67		Year-->	0	1	2	3	4	5	6	7	8	9	10
69	discounted O&M cost	$217,380,508		$9,966,369	$9,676,086	$9,394,259	$9,120,639	$8,854,990	$8,597,077	$8,346,677	$8,103,570	$7,867,544	$7,638,3
70	Discounted fertliser cost	$13,824,505		$684,773	$664,828	$645,464	$626,664	$608,412	$590,691	$573,486	$556,783	$540,566	$524,
71	discounted cost of health impact	$14,953,474		$630,741	$626,907	$615,830	$604,948	$594,259	$583,758	$573,443	$563,311	$553,357	$543,5
74	dicounted crop yeild	$1,546,261,140		$76,591,357	$74,360,541	$72,194,700	$70,091,942	$68,050,429	$66,068,378	$64,144,056	$62,275,782	$60,461,925	$58,700,8
75	dicounted fresh water value	$184,577,356		$9,142,718	$8,876,426	$8,617,889	$8,366,883	$8,123,187	$7,886,589	$7,656,883	$7,433,867	$7,217,346	$7,007,

Results

Costs-benefits results: summarise costs and benefits results (such as crops yield, capital and operational costs, total costs and benefits, net benefits, benefit costs ratio and internal return rate) in addition to land use per crops, total land used, total volume of water supply.



crop	elect Portion of Area %	Area	yield
		ha	US$/YEAR
wheat	25.00%	1032.891307	$8,006,973.41
barley	25.00%	1032.891307	$5,651,981.23
peas*			
broad beans*			
oat	30.00%	1239.469569	$7,846,833.95
potato	10.00%	413.1565229	$23,549,921.81
onion			
lettuce and Green-Leaf Crops	5.00%	206.5782615	$9,419,968.72
carrot	2.50%	103.2891307	$5,887,480.45
Radish	2.50%	103.2891307	$1,569,994.79
Millets			
tomato	20.00%	826.3130458	$16,955,943.70
water melon			
cucumber			
eggplant			
pepper			
cauliflower			
olive tree			
palm tree			
alfalfa*			

life cycle costs results

Discount Rate (%)-->	3%
Project Life (30 yrs max)-->	30
discounted costs	**US$**
capital costs	$536,200,000.0
O&M cost	$217,380,507.7
fertliser cost	$13,824,505.1
cost of health impact	$14,953,474.3
Total Discounted Costs	**$782,358,487.1**
Discounted benefits	**US$**
crop yeild	$1,546,261,139.7
fresh water value	$184,577,356.2
Total Discounted Benfits	**$1,730,838,495.9**
Net Present Value ---->	**$948,480,008.8**
Benefits/Costs Ratio--->	**2.212334**
internal return rate ---->	**13.9%**

water supply	septic tank+ (WSP)	**T4**
irrigation water volume	cubic m /year	30.24
total area	ha	4131.56523

Annex 5

Data collection methods

A5.1 Objective

- To collect information related to water resources management, water supply, agricultural activities, and wastewater collecting, disposal and treatment facilities in the city.
- To collect detailed data on current farming practices including crop types, current irrigation water sources, current fertilizer use, post-harvesting practices in order to form the basis of the baseline scenario currently in operation in Misurata.

A5.2 Data collection methods

The research will be based on both primary and secondary data from a case study that will be carried out in Misurata in Libya. In order to obtain good quality data, a range of different sources will be used with a different approach being required depending on the information needed and the target group. **Error! Reference source not found.** illustrates the different alternative approach to collect the required data, which 1, 2, and 3 represents the first, second and third alternatives respectively for collecting these data.

A5.3 Collection of Primary Data

Primary data will be obtained through a number of different approaches:

- Structured interviews with farmers in Misrata
- Open questionnaires with key informants including government officials, treatment plant operators and waste disposal agency workers
- Field tests – depending on the time and facilities available it may be possible to carry out a number of sampling and analysis tasks.

A5.3.1 Structured Interview with Farmer

Farmers will be asked through structured interview to provide information about their agricultural practices which includes information related to:

- Crops (type- yields- seasons)
- Irrigation systems(type-cost-time- frequency)
- Agriculture practice (labour or mechanization)
- Harvesting and marketing practises
- Fertilizer applications(type-cost)
- Water supply (source, quality and cost)

It is anticipated that farmers will be interviewed on their own farms, thereby avoiding any need for them to travel and minimising disruption to their routine. The number of visits to individual farmers will depend on whether they agree to be interviewed on the first visit or whether they require time to review the information given and make a decision. In the latter case, this will mean a follow-up visit to carry out the interview meaning a total of two visits. It is anticipated that the interview will take approximately 1 hour.

Target population

The research will focus on providing data on viable alternatives to current water supplies for agriculture. At present in Misrata, there is a project underway looking at the provision of water from the ‘man-made river’ for agricultural purpose. Information from this project includes a list of farms that will be included in this new supply network and. Therefore, these farms will be the ones that will be included in this study. As a result, farmers from agricultural project farms which are located in Al Dafinyah (248 farms) will be selected as the target population.

Sampling size

Due to the constraint of the time and the financial resources available for the study, not all the target farmers will be interviewed instead representative sample with a sufficient size will be used. This survey is not intended to be statistically representative rather the intention is to gather general information about agricultural practices in the area. Data collected from households will be triangulated with key informant interviews and secondary data. The estimated number of households to be interviewed is currently 30. Farming practices are relatively homogeneous in the area and, therefore, it is believed that this number will be sufficient.

Selecting the samples

There are two alternative options to select the sample. The first option is selecting the farm randomly from a list of farms- identity numbers. Each farm in the above location usually has identity number in the Ministry of agriculture and livestock in Misurata, and if the list of these numbers can be obtained simple random sampling can be easily used.

However, if access to this list became difficult, cluster sampling will be used; map of the above location will be divided into grids, each of these grids will be numbered and considerate as a cluster. The total number of randomly selected clusters will be equal to samples sizes, the first farm in each of these selected clusters will be chosen for the interview.

A5.3.2 Key informants

A number of key informants will be interviewed to provide information related to water resources management, water supply, agricultural activities, and wastewater collecting, disposal and treatment facilities in the city. Prior to undertaking the fieldwork, a number of organisations and authorities have been identified based on the required data. These organisations were identified based on the researcher's in-depth knowledge of the region and the organisational structure that currently exists. These organisations are listed below. Contact will be made with each organisation (rather than any individual), and it is anticipated that the organisation will determine, from the information requested who the most appropriate interviewee will be.

- Housing and infrastructure board (housing and infrastructure ministry)
- Engineering consulting office for utilities
- General Water and Sewage Company
- Misurata sewage treatment plant
- Wastewater Treatment Plant in Libyan Iron and Steel Complex
- General water authority (middle region)
- The authority for the utilization of Jabel Hasawna- Jefara Water system of the man-made river.
- Ministry of agriculture and livestock in Misurata
- Agriculture development committee

In additions to:

- treatment plant operators in their working place
- disposal agencies workers in their working place

It is anticipated that the process will involve and initial visit in person at their office to provide information relating to the research and a letter of introduction. The possible outcomes from the initial meeting may be:

- Granting of an interview straight away
- Granting of an interview with an appointment at a later date
- Request for time to review the information before agreeing to take part
- Key informant declines to take part.

Therefore, the number of visits will depend upon the decision of the key informant. The interview will be arranged at a time and place to suit the participant.

A5.3.3 Field tests

The purpose of this is to obtain data on the chemical and microbial quality of wastewater from a variety of sources including wastewater treatment facilities and soak-away tanks. This information is important in order to assess the ‘value’ of the wastewater in terms of nutrients and ‘risks’ associated with pathogens, salinity and heavy metals.

Chemical of wastewater from wastewater treatment and soak away tanks includes (EC or TDS, total N (NO3, NH4), P, K (this will be done by taking samples of wastewater from treatment facilities and soak away-tanks to local laboratory (University or other government laps)

Microbial test using “field kit” to measure total Fecal Coliforms or E-coli in wastewater from wastewater networks treatment facilities and soak away tanks.

Collection of secondary data

Where it is not possible to collect primary data, then secondary data sources will be used including both published and unpublished sources of data and information. It is anticipated that secondary data will be obtained through interviews with key informants to determine the availability of secondary data and the possibility of access to that data. The types of secondary data that may be available would be:

- Wastewater treatment facility data including types of treatment used, costs, etc.
- Wastewater quality data from laboratory reports
- Official documents and reports from related government departments and authorities including information on wastewater collection, sources of water supply, regional agricultural data.

Table1 Alternative methods for collecting required Data

Framework component		Required Data	Source of data				
			Secondary data		Primary data		
			From Libya	international source	Interview	key informants	Field tests
Agriculture Data	Health risk assessment (QMRA) AND Environmental risk assessment	Types of crops.	3		1	2	
		irrigation practice and technique	3		1	2	
		Agriculture practice (Labor or mechanization based)	3		1	2	
		Harvesting and marketing practices	3		1	2	
Wastewater data	Capital and operation cost	Current and future volume of wastewater	2			1	
	Health risk assessment (QMRA) AND Environmental risk assessment	Quality of raw wastewater: - Chemical tests - microbial tests	1	3 2			2 1
		Quality wastewater outflow from treatment plant - Chemical tests - Biological tests	2	3 2			1 1
		Quality wastewater outflow from soak-away tanks	2	3			1
Sewage network and treatment plants	Capital and operational cost	Treatment plants capacity	2			1	2
		Treatment technology	2	3		1	2
		Sewage collection systems	2			1	2

Framework component		**Required Data**	**Source of data**				
			Secondary data		**Primary data**		
			From Libya	**international source**	**Interview**	**key informants**	**Field tests**
Health data	Health risk assessment QMRA	Endemic Waterborne disease		1			
		Rate of mortality and morbidity due to above disease		1			
		Incidence of diseases		1			
		Diseases –infection ratio		1			
		Exposure (A possible route of transmission of causal pathogens)	2	3	1		
Economic data	Value of fresh water	Cost of water abstraction for irrigation: • Cost of water from manmade river • Cost of privet well (drilling and pumping) • Sea water desalination	2	3		1	
	Capital and Operational cost	Capital cost of wastewater treatment options	2	3		1	
	Capital and Operational cost	the cost of collection wastewater and distribution	2	3		1	
	Capital and Operational cost	Cost of operation and maintenance	2	3		1	
	Agriculture value	Cost of fertilizer	2	3	1		
	Agriculture value	Value of crops	2	3	1		

4. The first option
5. Second option
6. Third option

A.3.4 Key informant interview

The key informants will be interviewed mostly through open equations. The main purpose of the interview is to provide access to secondary data as well as given information or data that may not be documented. These data is divided into four themes include wastewater collecting and sewerage network, wastewater treatment plants, water supply for agriculture use, agriculture activities. Each of key informants will be capable of providing some of these data.

A5.4.1 Wastewater collecting and sewerage network

- Data regard of water consumes per capital
- Estimation of the wastewater volume generated in the city
- The proportion of the city been connected to sewerage network
- Information about soak away tanks includes: design and capacity, emptying methods, disposal methods and costs.
- Type of sewerage system, conditions, and information regards to capital costs and O&M costs.

A5.4.2 Wastewater treatment plants

- Number of treatment plants in the city
- Type of treatment
- Design capacity
- Current wastewater flow the plant receive daily
- The efficiency of the plants
- Data regards to capital costs, and operational and maintenance (O&M) costs.
- Data about wastewater quality analysis including (Chemical tests, Biological tests, from plant laboratory
- Disposal of wastewater effluence and sludge

A5.4.3 The main source of water supply for agriculture use

- Current situation of irrigation Water supply.
- Data regards to Water quality from different water sources
- Information about man-made river supply which include:
    - Water capacities for domestic and agriculture use
    - Costs of transfer meter cube of water to the city
    - Costs of undergoing project to supply farms from man- made rivers.

A5.4.4 Agriculture activities

- Agriculture and land use in the city
- Type and the classification of farms in the city

- Statistic about the number and the areas of the farms in the city
- Information regards to type of typical crops cultivated in city’s farms
- Data regards to yield and nutrients (or fertilizer) requirements of typical crops.

A5.5 The Farms’ Interview Guide

I would confirm that all information obtained as a result of this interview will be used for the purposes of fulfilling the PhD Thesis criteria, and in relevant future research. Also, all respondents / participants will remain anonymous and confidentiality of responses is guaranteed. The responding party has the right to withdraw from this process at any time.

Section 1 General information

1. Location:
   - ☐ AL DAFINYAH
   - ☐ TAMINA
   - ☐ KRARIM

2. Ownership
   - ☐ Farmer working in owned land
   - ☐ Farmer working in rented land
   - ☐ Farmer working for other
   - ☐ Others specify ( )

3. Farm Area:
   - ☐ Less than 10 hectares
   - ☐ Between 10-20 hectares
   - ☐ More than 20 -30 hectares

4. Thinking about the current spring- summer season (2015) and last fall winter season(2014-15), in each season, did you cultivate all the land?
   - ☐ Yes go to section 2
   - ☐ No, go to Q5

5. How much of your land did you usually cultivate? (PLEASE ENTER UNITS)
   - ☐

6. Can you tell us why you do not cultivate all the land?
   - ☐ Due to lake of water supply
   - ☐ Due to soil fertility issue
   - ☐ Other specify:

Section 2: crops

1. Please think about the crops you have grown on your land during current spring – summer (2015) season and previous fall-winter season (2014-15). What kinds of crops did you grow in different seasons, and what is the yield (kg/ha)? SELECT ALL CROPS APPLY IN EACH SEASON

crops	spring –summer season		fall-winter season	
	Have you grown this? 1.Yes 2.No	Yield (kg/ha)	Have you grown this? 1.Yes 2.No	Yield (kg/ha)
Fodder:				
☐ alfalfa				
☐ oat				
☐ other specify ( )				
Grains:				
☐ wheat				
☐ barley				
☐ Millets				
☐ maize				
☐ other specify ( )				
Vegetable:				
☐ beas				
☐ broad beans				
☐ onion				
☐ lettuce and Green-Leaf Crops				
☐ tomato				
☐ carrot				
☐ watermelon				
☐ potato				
☐ cucumber				
☐ eggplant				
☐ pepper				
☐ cabbage				
☐ cauliflower				
☐ Radish				
☐ other specify ☐ ( )				
☐ Tree:				
Palm tree				
☐ Olive tree				
☐ other specify ☐ ( )				

2. Thinking about your profit, which of the three important crops do you consider for your profit? (SELECT AND RANK THEM FROM 1 TO 3 AS THE MOST IMPORTANT HAS RANKED NUMBER 1)

Crops :	Rank
☐ fodder	
☐ grains	
☐ vegetable	
☐ palm tree	
☐ Oliver tree	
☐ Almond tree	
☐ Others (specify)	

Section3: Water supply

3. From where do you get your irrigation water?
   - ☐ Privet well → go to Q4
   - ☐ Man-made River → go to Q8
   - ☐ Other (specify) → go to Q8
4. I would like to ask you about the costs of the well, how much cost you

☐ Drilling the well	
☐ Casing and riser pipe	
☐ Pump and its install	
☐ Connect to electricity supply	

5. How many well you have drill before you could get the good ground water quality?
   - ☐ It is the first one
   - ☐ Two
   - ☐ More than 2 (specify)
6. Please think about last two year can you tell us about the regular maintenance problem of your well and provide us an estimation of the average costs?

Problem	Cost of maintenance
☐	☐
☐	☐
☐	☐
☐	☐
☐	☐

7. I would like to know about the energy cost of pumping the water from the well, think about current spring-summer (2015) season and last fall-winter (2014-15) season can you tell as in average how many hours the pumping system is working per day?

Season	Pump Working hours
Spring -summer	
Fall -winter	

8. Think about last year how much did you pay for your water bill?

☐ Nothing
☐ LYD

9. Thinking about the salinity of your water, how do you consider your irrigation water quality?

☐ Fresh
☐ Morden
☐ Morden Salty
☐ Very salty

10. What is your irrigation system?

☐ Furrow irrigation
☐ Sprinkle irrigation
☐ Drip irrigation
☐ Combination of different systems

11. How much have cost you to install current irrigation systems?

☐

Think about last two year can you tell us about the regular maintenance problems of your irrigation system and provide us an estimation of the average costs?

Problem	Cost of maintenance
☐	
☐	
☐	
☐	
☐	
☐	
☐	

Section 4: Fertiliser

12. Please think about the crops you have grown on your land during current spring –summer season (2015) and previous fall-winter season (2014-15) and answer the following questions:

Crops	Have you grown this? 1. Yes 2. No	Did you use any chemical fertilizer for growing this crop? 1. Yes 2. No	Did you use the manure for fertiliser? 1. Yes 2. No	Did you use other organic amendments for fertiliser? 1. Yes 2. No
Fodder:				
☐ alfalfa				
☐ oat				
☐ other specify ( )				
Grains:				
☐ wheat				
☐ barley				
☐ Millets				
☐ maize				
☐ other specify ( )				
Vegetable:				
☐ beas				
☐ broad beans				
☐ onion				
☐ lettuce and Green-Leaf Crops				
☐ tomato				
☐ carrot				
☐ water melon				
☐ potato				
☐ cucumber				
☐ eggplant				
☐ squash courgette				

☐ pepper				
☐ cabbage				
☐ cauliflower				
☐ Radish				
☐ other specify ☐ ( )				
Tree:				
☐ Palm tree				
☐ Olive tree				
☐ Almond tree				
☐ other specify ( )				

Again think about the crops you have grown on your land during current spring –summer season (2015) and previous fall-winter season (2014-15) and answer the following questions:

13. What type of manure have you used?

☐ No, I did not use manure → go to Q17
☐ manures Poultry
☐ manures sheep
☐ manures beef
☐ other (specify) ----------------------

14. What form was the manure?

☐ Fresh bulk
☐ Semi-fresh bulk
☐ Dry granulated

15. How much did you pay for the manure?

☐ Free
☐ LYD/ ton

16. What type of other organic amendment did you apply?

☐ No, I did not use organic amendment → go to Q19
☐ Yes, compost
☐ Yes, biosolid
☐ Yes, other (specify) ------------------------

17. How much did you pay for the organic amendment?

☐ Free
☐ LYD/ ton
☐

18. Which of these chemical fertilisers have you applied? TICK ALL TYPES YOU USED

	N-Fertilizer	P- fertilizer	K-fertilizer
☐ Urea			
☐ Urea-ammonium nitrate (UAN)			
☐ Ammonium sulphate			
☐ Ammonium nitrate			
☐ Monoammonium phosphate			
☐ Diammonium phosphate			
☐ Urea ammonium phosphate			
☐ Triple superphosphate			
☐ Superphosphate			
☐ Potassium nitrate			
☐ Potassium sulphate			
☐ Others(specify)			

19. Please think about your fertilizer use during the current spring –summer season (2015) and previous fall-winter season (2014-15). I will now ask you some questions on the quantity of fertilizer you used. Please tell me how many kilograms of fertilizers you used in the different agricultural seasons.

	Unit	N-Fertilizer	P-fertilizer	K-fertilizer	Organic amendment	Manure
Spring- summer season	kg					
Fall-winter season	kg					

Section 5: Agricultural practices

20. What is the farming practice in your farm?
    - ☐ Highly rely on machines.
    - ☐ Labour intensive.
    - ☐ Both

21. What of these protective wear you normally use when you work in the field?
    - ☐ Gloves
    - ☐ Footwear(Gumboots)
    - ☐ Overalls
    - ☐ Other,(specify)……………………….

Please think about the crops you have grown on your land during current spring –summer season (2015) fall-winter season (2014-15) and answer the following questions:

22. Have you ceased irrigation before harvesting of crops?
    - ☐ No → go Q24
    - ☐ Yes → go Q23
23. How many days you ceased irrigation for:

Fodder & Grains:

- ☐ Less than week
- ☐ Week
- ☐ More than week

Vegetable:

- ☐ One day
- ☐ Two days
- ☐ Less than week

24. For vegetable crops, do you store the harvested crops before you take them to market, how do you store them?
    - ☐ No
    - ☐ Yes, Overnight storage in baskets
    - ☐ Yes, in cool storage.
25. For vegetable and fruit crops, what of the following Produce preparation you normally do before you take them to market, what do you do? You can select more than one
    - ☐ Rinsing crops with clean water
    - ☐ Washing with running tap water
    - ☐ Removing outer leaves of lettuces etc
    - ☐ None

Section 6: farmer perception regarding the reuse of wastewater as irrigation water supply

As you may know that wastewater reuse in agriculture is a widespread practice. To a large extent, wastewater can be considered as a reliable source of water and nutrients that are available all year around. Wide availability and fertilising properties make it valuable particularly in arid and semi- arid climates.

In this section, I would like to know your perception regarding the reusing wastewater as your irrigation supply.

But before the question, please hold these ten stones in your hand, and use them to answer the questions I am about to ask you, by putting them down on the ground. You may put down on the ground as many stones as you feel in order to answer the question according to your opinion. Let us practice a few questions. For example:

- Do you think the sun will rise tomorrow morning? We know that the sun rises every day; so in this case, you would put all 10 stones on the ground.
- Do you think two suns will rise tomorrow morning? We know that two suns will certainly not rise tomorrow, so in this case, you would not put down any stones.
- Do you think it would be windy next week? It is an event that may or may not occur. If you feel that it is less likely to windy, then you may put down 2 or 3 stones. If you feel it is very likely to rain, you may put down 7 or 8 stones.

Now, Please tell us your opinion, using the stones provided to you. The more stones you put on the ground, the more you agree with the statement. If you put all ten stones on the ground that means that you completely agree with the statement.

1. I would use a wastewater if it increases the opportunity to cultivate more of my land	
2. I would use a wastewater if it has sufficient N-P-K and substitute fertiliser use	
3. I would use a wastewater if it’s price is the same as my current supply	
4. I would use wastewater if does not affect the quality and marketability of the products	
5. I would use wastewater if it does not restrict the current cropping pattern	
6. I would use a wastewater if it is certified by the government.	
7. I would use a wastewater if it provides reliable supply and easier to access	
8. I would use a wastewater if credit for buying it was made available	
9. I would use a wastewater if it is safe to handle and use	
10. I would buy a wastewater if my friends/neighbours are also reusing it.	
11. I would only use wastewater if there is no alternative	

A5.6 Field tests

The purpose of this is to obtain data on the chemical and microbial quality of wastewater from a variety of sources including wastewater treatment facilities and soak-away tanks. This information is important in order to assess the 'value' of the wastewater in terms of nutrients and 'risks' associated with pathogens, salinity and heavy metals. Table (2) summarise the main wastewater analyses that is required in order to achieve the objectives of this study.

Table 2: Laboratory analysis for wastewater characterization

chemical analysis of wastewater	Microbial analysis of wastewater
1. SS 2. BOD 3. TDS 4. EC 5. Nitrogen: • TKN=Ammonia+ ON • Nitrate+ nitrite 6. Phosphate • Phosphorus, total 7. Potassium	Fecal Coliform or E- coli

A5.6.1 Requirement tools and material for sampling

The following list provides general requirements for sampling wastewater. Details of the type of container used for the collection and storage of samples are given in table 3

- Personal protective equipment Gear (such as waterproof clothing, rubber boots , Gloves Safety face mask, and glasses)
- Disinfection solution
- Sampling Equipment
- Sample Bottles with labels and documentation
- Distilled water
- Cooler with ice
- first aid kit

Table 3: Techniques generally suitable for the preservation of samples for chemical and microbiological analysis

chemical analysis of wastewater			
Parameters	**Container**	**Preservation**[1]	**Max recommended Holding time**
EC	500 mL polyethylene Container	Ice-4ºC	28days
Solids series(TS TSS, TDS,TVSS)	1 liter polyethylene Container	Ice-4ºC	7days
BOD5	1 liter polyethylene Container	Ice-4ºC	48hr
Nutrients TKN, Ammonia NO3+ NO2-N	500 mL polyethylene Container	Ice-4ºC, Acidified to pH<2 with H2SO4	28days
Phosphorus, total	500 mL polyethylene Container	Ice-4ºC, Acidified to pH<2 with H2SO4*	28 days
Potassium	100 ml polyethylene Container	Acidified to pH<2 with HNO3**	28days
microbiological analysis of wastewater			
parameters	**Materials**	**Preservation**	**Max recommended Holding time**
fecal coliform: C- coli	250ml sterilized polyethylene container	ICE- 4°C	6hr

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*H_2SO_4 - Sulfuric Acid used as a preservative must be present at concentrations ≤ 0.35% by weight

**HNO_3 - Nitric Acid used as a preservative must be present at concentrations ≤ 0.15% by weight

A.3.6.2 Guidance on the preservation and handling of wastewater samples

I. **Precautions to be taken**

- Use proper Personal Protection Equipment
- A clean pair of new, non-powdered, disposable gloves will be worn each time a different location is sampled and the gloves should be donned immediately prior to sampling. The gloves should not come in contact with the media being sampled and should be changed any time during sample collection when their cleanliness is compromised.
- Never enter confined spaces
- Be cautious of toxic gases
- Disinfection of hands and any equipment after finishing of sampling

II. Container preparation

- If disposable or single-use containers cannot be used, it is preferable to reserve a set of containers for a particular determined, thereby minimizing risks of cross-contamination.
- It may be necessary to wash new containers with water containing a detergent, in order to remove dust and residues of packing materials, followed by thorough rinsing with water of an appropriate quality(Distilled water)

III. Filling the container

- Wastewater samples will typically be collected by directly filling the sample container (using appropriate containers as described in table 3).
- To obtain a representative wastewater, the sample should be collected where the wastewater is well mixed (typically where the turbulence is at a maximum and the possibility of solids settling is minimized).
- Fill the container completely and stopper it in such a way that there is no air space above the sample. This reduces interaction with the gas phase, and minimizes agitation of the sample during transport

IV. Handling and preservation of samples

- Containers holding samples should be protected and sealed in such a way that samples do not deteriorate and do not lose any of their constituents during transport.
- All samples requiring preservation must be preserved as soon as practically possible, ideally immediately at the time of sample collection.
- In the case of using Ice, Sufficient amount of ice must be placed in the transport container to ensure ice is still present when the samples are received at the lab

V. Identification of samples

- Sample containers should be labelled in a clear and unambiguous manner that is durable. Also at the time of sampling, appropriate field sheets (that contains details such as date and time of sampling, sampler name and contact details, nature and the amount of preservative added) should be completed.

VI. Reception of samples

- Laboratory staff should establish whether samples underwent cooling during transportation and if possible whether a sample environmental temperature between 1 °C to 5 °C was maintained.

- In all cases, and especially when a “chain of custody” process needs to be established, the count of sample containers received in the laboratory should be verified against the number of sample bottles provided for each sample.