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The Reliability of Sustainable Water System and Infrastructure in Kuwait

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The Reliability of Sustainable Water System and Infrastructure in Kuwait

by

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Dedication

Dedicated to my parents and wife who helped me in

Becoming in what I am right now. My son I hope this inspires you to become a greater person than I am today.

I hope this work Satisfy their expectation of me. They have been a great support for me in my entire career.

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Duaij AlRukaibi

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The Reliability of Sustainable Water System and

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The University of Texas at Austin, 2013

Supervisor: Daene McKinney

Abstract

Economic, environmental, and social components form the structure of sustainable development and characterize the positive or negative trends in sustainability, which are a unique sustainable index. The Kuwait water system is considered a case study in this research to develop a methodology for identifying sustainable water systems, especially in terms of the high water demand per capita and high supply of desalinated water. This research provides certain answers to the following issues: 1) the sustainable water system path for Kuwait is unknown; 2) the low price of water for consumers is a reason for the wastefulness in water consumption in Kuwait; 3) there is no sustainable model for the water infrastructure in Kuwait to control and maintain its system; and 4) building a new desalination plant will put pressure on reducing the oil products' revenues that are export to global market. Sustainable water supply systems

must be designed and operated so as to accomplish the following: minimize energy use, maximize efficient use of water as a resource, and limit (or even decrease) the associated environmental impacts of water usage. Increasing the production of water and the associated infrastructure are not necessarily sustainable solutions to the challenges of population growth. Consequently, this research provides the following solutions to work together in parallel: 1) Model Urban City (MUC); 2) Sustainable Water System and Infrastructure of Kuwait (SWSIK); 3) Sustainable Kuwait Index (SKI); and 4) reform the current water price policy in Kuwait. This research is dependent on three foundations—MUC, SWSIK, and SKI—to characterize sustainability in Kuwait and to analyze the environmental and economic impacts under three different water price scenarios during the period of 2013–2017. Numerical modeling, Infowater application, is used to connect the data with Arc GIS software to monitor the progress toward sustainability for 78 areas in the country. The Sustainable Water System and Infrastructure of Kuwait (SWSIK) tool is developed in this study and provides a comprehensive tool that analyzes water consumption due to water price policies to determine the energy needed from fossil fuels, the energy costs, and the environmental impacts. The Sustainable Kuwait Index (SKI) is a unique numeric value of 16 indicators. The sustainability indicators for the Kuwait water system are classified into two main categories: environmental and socio-economic, in which the resources, infrastructure, and capacity are components in the environmental category. SKI is determined for urban areas in Kuwait between 2008 and 2012, characterizing the state of sustainability. Population growth and new urban development push decision makers to find alternative solutions—such as reforming water price policies—to reduce wasteful water consumption in both normal and critical times. Two water price policy scenarios were proposed to be implemented, instead of the current water price policy (0.624 per m^3). The first scenario involves a constant price charged for water consumption at \$1 per m^3. The second scenario involves a different structure to schedule water price: free allowance (150 L/C/day) followed by a constant price charged for water consumption over 150 L at \$1.6 per m^3. The time frame to test both proposal scenarios is between 2013 and 2017. In order to get water for free, the second proposal scenario encourages consumers to consume water wisely. This proposal scenario is acceptable for both consumers and policymakers, and it provides economic and environment benefits for both sides. The second scenario will postpone the need for new desalination plants until 2023. SKI scores are determined for the three water price scenarios during the proposal time (2013–2017) for 78 urban areas in Kuwait. By applying the first scenario (\$1.0 per m^3), the Kuwait government will save almost 5 million barrels per year from oil products (crude oil, gas oil, and HFO) and reduce natural gas usage by 31% per year. On the other hand, the second scenario can reduce the usage of oil products and natural gas in desalination plants by 26% per year. CO_2, SO_2, and NO_2 emissions under the first and second scenarios were reduced in the range between 26% and 33% per year. Overall, a shortage will occur in 2014 if the Kuwait government does not change the water price structure. The current water price (\$0.624 per m^3) gives zero economic value to consumers. As a consequence, water bills were not collected effectively due to the low cost. The first scenario, which charges \$1 per m^3, might be unacceptable for consumers due to the stigma associated with increasing prices. The second scenario, however, satisfies the sustainability conditions, which are: 1) to save the environment; 2) to reduce costs; 3) to be acceptable to society; and 4) to achieve policymakers' goals. The results obtained in this research are intended to promote water system management and provide sustainable indicators to evaluate the development of a sustainable of water infrastructure in Kuwait.

Keywords: sustainable development, Sustainable Kuwait Index, indicators, water price, shortage, Infrastructure.

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CHAPTER 1: Introduction

Engineering planning and management play an important role in sustaining, rehabilitating, integrating, and developing infrastructure networks. The sustainable development will have a reflective impact on all types of urban infrastructures. The new approach to planning is to anticipate the changes that an uncertain future may bring by using a range of considerations in planning for infrastructure in the face of many vulnerabilities and risks. Modern, maintainable, reliable, and sustainable public infrastructure is critically important, whether it takes the form of water-treatment facilities, water networks, bridges and roads, public transit, utilities, or the electric grid. Sustainable infrastructure is not only a reflection of a community's long-term resilience but also evidence of its value across the areas of environment, economics, and society. Sustainable development has become the main framework to promote natural resource systems for urban cities in multi-dimensions. In response to population growth, limited natural resources, and increases in economic resources and technology, it is necessary to have engineering tools and techniques to integrate all of the components without compromising any of them. Stress on the world's finite resources, such as land, water, materials, food, and energy, is increasing due to population growth and economic development. To preserve and improve the quality and quantity of our resources, we need to develop a sustainable framework in which our developments meet our requirements for natural resources, energy, food, transportation, and waste recycling and decrease the growing social and economic inequities.

Sustainability is the main framework that has emerged as a planning and management concept and has commonly been applied to urban development in the fields of environmental, social, and economic planning, which are the triple bottom line of sustainability. In addition, sustainable development (SD) has become a tool in engineering to integrate natural resources. It is most popularly and clearly defined in the Brundtland report as development that meets the demands of the current generation without compromising the ability of future generations to meet their own demands (WCED 1987). Sustainable infrastructure provides and maintains physical infrastructure (water supply systems, in this case) to enable reliable and accurate consumer use for the predictable future with attention to the infrastructure systems themselves, taking into account the adequacy of these systems to serve an increasing population, satisfy public-service demands, remain in satisfactory working order, and be supported by reliable economic resources.

Global sustainable development is not possible without analyzing and monitoring the water system. Water supply and distribution systems play an important role in achieving the ultimate goal of sustainability. Sustainable water-supply systems must be designed and operated so as to accomplish the following: minimize energy use, maximize efficient use of water as a resource, and limit (or even decrease) the associated environmental impacts of water usage. Sustainable water infrastructure is vital to providing clean and safe freshwater and helping to ensure environmental, economic, and social health. Sustainable development is multidimensional development that achieves the satisfaction of human requirements and at the same time considers improvement of the quality and quantity of resources with limits to allow them to renew themselves. Looking toward a future with increasing demands on water resources, it is clear that coordinated water planning will be an ongoing need. Sustainable development refers to a wide range of issues that involve an integrated approach to the management of the economy and environment and concern areas of human and institutional capacity. In order to manage a water system and its distribution network, the decision maker needs information to use sustainable development as a planning vision, including information on the current stage of progress, trends, pressure points, and the impacts of interventions. Indicators enable decision makers and policy makers to see if they are on the right track and to help them monitor progress toward sustainable development.

The concepts of supply and demand deal with prediction, management, and planning of the quantity and quality of water in the surface (lakes, rivers, and seas) and subsurface (aquifer) systems. Natural resources planners and managers are concerned with two parameters, supply and demand, within specific regions. They also develop and integrate natural resources, trying to make them continuous in supply by applying different methods and techniques. A significant increase in demand for water is expected during the next few decades based on population growth all over the world and increasing environmental pollution, which will likely contribute to poor quality of the available water resources. These will push decision makers to find alternative solutions for the supply of water in normal and critical times. In addition, they will strive to develop efficient and reliable water-distribution systems based on standard global guidelines. Increasing the production of water and its infrastructure are no longer reasonable solutions to the challenges of a growing population, and sustainability can better be attained by optimizing both supply and demand at the same time by using software that considers all system components and allows the consideration of many scenarios for allocating scarce supply to growing demands and managing the water sources. Water Distribution Network (WDN) software will contribute positively to optimizing water supply and demand in the state of Kuwait and will aid in developing water systems that manage the consumption and supply of water in a sustainable manner. Geographic information system (GIS) databases have already been built for the water system of Kuwait. Using ArcGIS and WDN software will help in developing many scenarios to increase water production wisely and reduce the demand associated with water infrastructure and climate change. WDN software with GIS data has the capability to improve the water system and guide investment by strategically analyzing and projecting the network demand distribution for various scenarios.

Water system cycle includes supply source, water distribution network (WDN), water price policy, non-water policy (efficient water devices, educational conservation plans) and wastewater treatment plants. The process of water system cycle starts from water production and go through WDN under some hydraulics and policies constrains to deliver water to household. The final destination for water used in households is the wastewater plants to treat them based on the engineering standards. This study is focusing in the saving in reducing water consumption by reform the current water price policy. As consequences of reducing water consumption, wastewater treatment plants will reduce the production. Only water price policy and its effects on reducing the wastefulness in water consumption is considered in saving to government budget with few water demand models incorporating economic and environmental impacts. Then, this study will provide the benefits of water saving due to only reducing water consumption that can invest in developing infrastructure. The saving of water reduction can invest in improve water distribution network, build water storages, educational awareness, distribute efficient devices.

1.1. Statement of Problem

The water system of Kuwait suffers from a lack of a comprehensive framework for management and planning. Therefore, the triple bottom line of sustainable development (environmental, economic, and social considerations) should be integrated with the infrastructure plans in the same framework to provide optimal and up-to-date results to decision makers. To fully understand how to integrating the sustainability with water system planning and management, it is essential first understand what the options involve. A distorted picture of integrated management can arise by only focusing on the supply management option. A clear definition for differentiation between water demand management and supply management and how each contributes to integrated water planning and management framework are necessary steps. High water consumption per capita is emerging in Kuwait; this is a critical issue that needs to be resolved to avoid any interrupting or shortage in the water supply.

Water price policy has never changed in Kuwait. The supply management was the preferred option to meet the consumers' water demand. Population growth, increasing urbanization, rising temperatures, improvements in the standard of living, and the twofold increase in household every five years with ignoring the role of water demand framework, that have led Kuwait and other GCC countries to be considered on the top of the list of the countries in the world that consume the greatest water per capita (The Peninsula, 2009). Current water price policy has not proven to limit the wasteful in water consumption. Indeed, it encourages consumers to use water without limit. Because water price is heavily subsidized in Kuwait, the current practice of water pricing provides zero economic value for consumers. By maintaining the same consumption behaviors, Kuwait will experience an impact on the oil products' revenues that are exported to the global market, as well as an increase in the environmental impact due to the burning of fossil fuels in desalination plants. Immediate intervention to resolve the impact of low water price can be obtained by initiating integrated sustainable framework. An integrated system helps to reduce errors and increases the chances of accurately forecasting the demands of consumers. In addition, developing an integrated framework has the potential to connect the sustainable development (SD) components (infrastructure, water system, population demands, economic, and social factors) to help narrow the gaps between the components and characterize the vulnerability and reliability of the water system in Kuwait.

The sustainability of the water system in Kuwait is questionable. There is no evidence to show whether Kuwait is going toward or away from sustainability at this time, so indicators of sustainable development are needed. Additionally, it is necessary to have the ability to track the progress of development to determine which actions should or should not be taken in an effort to make the urban infrastructures in Kuwait sustainable. Indicators can provide many benefits when used as metrics to measure the status of sustainability, such as the prediction of future requirements, performance of targets, and warning systems for the country. Therefore, sustainability can be achieved when (Bell et al., 2005):

- The rate of using water resources (conventional and non-conventional) does not surpass the rate of future regeneration
- The rate of using non-renewable natural resources does not surpass the rate of sustainable substitutes
- The pollutant emissions do not surpass the capacity of environment to absorb and reduce them harmless (Do not exceed the standard value for the environment)

The water distribution network in Kuwait has been designed based on the best global standards to deliver water in terms of minimal water loss and fixed pressure for each region. Water infrastructure in Kuwait has been classified into 10 zones, based on elevation and water head in the pipe networks that can receive water from various sources. The current water distribution network has two methods for supplying water to the households in Kuwait. The first type is directly from the main sources (reservoirs). Also, water towers play a sustaining role in terms of balancing pressure in water distribution network. Recently, the Ministry of Electricity and Water, the only authority supplying water in Kuwait, switched to a second method of supplying water to households by providing elevated towers that receive fresh water directly from water storage sources. This type of water supply has the advantage of being able to provide almost constant pressure during the day. On other hand, there are uncertainties of the efficiency and durability of the water infrastructure with the potential increase in water demand. Nevertheless, the advancement in knowledge of water system needs a sustainable model, such as Arc GIS to monitor water demand due to population growth and the expanding in water infrastructure. Also, it needs an integrated water planning framework that analyzes and evaluates the economic and environmental perspectives for supply and demand options.

This research provides answers to the following questions:

1. Is Kuwait moving toward or away from a sustainable water system?
2. Can water consumption in Kuwait be reduced? If so, how? When?
3. With continuing increases in water demand in Kuwait, will Kuwait face an anticipated water shortage? If so, when?
4. Is the water infrastructure in Kuwait adequate now and will it be in the future? Would a new desalination plant solve the anticipated water shortage?

1.2. Dissertation Statement

The research's questions demonstrate the issues that drifting this research to find which Pricing form and sustainable solutions will effectively deliver greater economic, social, and environmental coherence in the region and neighborhood. The basic hypothesis of this study is that the current water price policy is the reason for high water consumption in Kuwait and that it needs to be reformed by the demand management framework. This study tries to prove theoretically that reforming the water price structure can cause to save the main nation's income (i.e., fossil fuels) in Kuwait, diminish the wastefulness in water consumption, and reduce the environmental emissions from desalination plants. In addition, water demand models were developed to estimate water usage at alternative water price scenarios. Although water demand is inelastic, water demand models are tested to show that water demand is sensitive to the water price. The magnitude of sensitivity is important to compare with previous studies in region. Alternative proposals for water price policies are presented to resolve the practice of low economic value for water product. The proposal of water price scenarios are stimulated by water demand models that have been adopted from previous studies that have the same circumstance of Kuwait. Statistical analyses test the correlation between the previous water demand models with Kuwait's data set. Overall, the approach of this study evaluates and tests the analytical results to reform the water price policy by providing sustainable solutions that intergrade water planning and management in Kuwait.

1.3. The Research Scope and Limitations

Countries in the Middle East face several challenges in ensuring water security, including how to maintain it and reduce the wasteful of water consumption. In oil-rich countries in this region (e.g., Gulf Cooperation Council [GCC] countries), the supply approach is the preferred option to satisfy water demand. This study focuses on Kuwait as case study. The economy of Kuwait is primarily reliant on the revenue of oil products that are exported to the global market. Continuing the manner of water consumption will put pressure on increasing the demand on fossil fuels to generate the energy needed for desalinated water. A consequence of this high demand on fossil fuels is going to downsize oil products' revenues that are exported. Oil products revenues are the backbone of the economy of the GCC. To avoid reducing the production of oil for export, water demand management should consider a solution to eliminate the wastefulness in water consumption. The results of this scope can be beneficial for countries that have similar circumstances. This study is bounded by time and policy limitations. First, the proposal of water price scenarios has a certain time frame (2013–2017), five years, due to the uncertainty of predicting oil products' prices in the global market for the long run. Furthermore, the time frame is reasonable to predict and project water consumption based on fossil fuels source, especially with possibility of switching to a new energy source such as solar energy by 2020.

This study scope is to reform water consumption behaviors in a region that is located in an arid area and that is primarily dependent on non- conventional water resources. Second, due to the fact that there has been no change in water price, price variation does not exist in Kuwait. So, this research looks to countries that have the same situations and has adapted their water demand models to be correlated with Kuwait's data. The water demand model of the case study, Kuwait, involves testing theoretically the correlated consumption behaviors, and these behaviors may or may not reflect the behaviors of similar entities. In addition to the previous limitations, Kuwait and GCC countries have special situations regarding the high incomes and high potential of the government to subsidize certain products. Subsequently, any attempt from the government to increase income or privileges for citizens or non-citizens (residents) will increase demand and minimize the economic value for water price. The final limitation to increase the validation of this study is that the range of sustainable water prices has to be applicable, anyone has to be able to afford it, and it has to be beneficial to diminish the wastefulness in water consumption. To fully understand the value of sustainable water price, it is necessary to define the range of this price value (minimum and maximum values). A sustainable water price is located between subsidized and equilibrium prices. A sustainable water price provides the minimum requirement of water volume (150–200 L/c/day) at a subsidized price, and for any consumption over that, it charges by a higher price less than the equilibrium price. The maximum value of water price is called the equilibrium price, which is when the water supply is equivalent to the water demand. But the government contributes to protecting its consumers and to providing water an acceptable price by subsidizing the equilibrium price (Lee, 2009). Thus, sustainable water price is in range between subsidized price and equilibrium price and varying based on the water price structure.

1.4. Statement of Objectives

The goal of the research is to provide a sustainability framework for water systems that can monitor, predict, and analyze water deficit and infrastructure issues related to water distribution networks and sustainable development terminologies. The research also shows the role of water pricing policy in reducing wastefulness in water consumption by applying different water pricing scenarios to reach a final goal, which is to design a sustainable water infrastructure framework for a modern city, save the nation's main income (i.e., fossil fuels), and reduce environmental impacts. The priority to reform the water price policy is to shift consumption behaviors to be more sustainable consumption behaviors. This can be obtained by changing the structure of charging water in Kuwait. In addition, the goal of reforming the practice of the current water price policy is to accomplish the following:

- ➢ Reduce fossil fuels usage in desalination plants
- ➢ Delay the necessity to build a new desalination plants
- ➢ Diminish the environmental impacts such as air pollution and high salinity of sea
- ➢ Eliminate the wastefulness in water consumption

The following are objectives to achieve the research goal:

- **Objective 1:** Develop environmental and socio-economic indicators for the water system.
- **Objective 2:** Visualize urban cities in Kuwait with a sustainable index, called SKI.
- **Objective 3:** Develop a geodatabase in ArcGIS, called Model Urban City (MUC), for use in developing the sustainability index and the sustainability analysis tool
- **Objective 4:** Develop the Sustainable Water System and Infrastructure of Kuwait (SWSIK) to be used as an analysis tool in ArcGIS

- **Objective 5:** Reform the current practice of water price scheduling by providing alternative water price scenarios to eliminate the wastefulness in water consumption

The Sustainable Water System and Infrastructure of Kuwait (SWSIK) tool is developed in this research and provides a comprehensive framework to: (1) measure water system performance; (2) forecast water supply and capacity needed to support future growth; (3) and identify national solutions to water needs based on a sustainability index and its indicators. The SWSIK tool is connected to the WDN to analyze performance under current and future situations. Overall, using the SWSIK tool can indicate the vulnerability, reliability, and best connectivity for the current water system. As for making a future prediction, it can define the economic and environmental aspects for water system policy and compare it with current policy condition. The purpose of the SWSIK is to provide sustainable tool that aids to evaluate water policies scenarios in terms of economic and environment perspectives.

This research will initiate and create a group of indicators to represent the current state of sustainability of the Kuwait water system and its infrastructure. A sustainability index is the formation of a single indicator from a large number of possible indicators as a unique numeric value. Also, it is easier to deliver the information and results with an index that represents the trend of sustainable development in the region. Infrastructure plays a critical role in the water system (supply and demand). Numerical modeling (MUC) is used to connect the data with GIS software to monitor the progress toward sustainability based on the WDN parameters. The previous sustainable solutions (MUC, SWSIK, SKI) have the ability to test the feasibility of the proposal of water price scenarios. Reform the current water price in Kuwait is first step toward integrated water system framework. The purpose of this research is to move beyond the vision of the current water distribution system in terms of performance, climate change influence, and population growth. Alternative water price structures are proposed to evaluate the reduction in water consumption. The consequences of reduced water overconsumption is measured and evaluated in terms of the impact on environmental, economic, social, and water-infrastructural considerations.

Next chapter illustrates the holistic background of water system and others variables that related to water in Kuwait. Overall, background chapter is the data bank of this research.

CHAPTER 2: Background on Kuwait Water

Kuwait, one of the GCC countries (with Bahrain, the Kingdom of Saudi Arabia, Qatar, the United Arab Emirates, and Oman), is located in the northwestern portion of the Arabian Gulf. It covers an area of 17,818 square kilometers and has a total coastline of 499 kilometers. Its geographic coordinates are (29º30' N, 45º45' E) and it shares borders with Iraq to the north and northwest, the Kingdom of Saudi Arabia (KSA) to the south and southwest. The Arabian Gulf bounds Kuwait to the east. There are nine islands in the country's territorial waters: Warbah, Bubiyan, Maskan, Failaka, Awhah, Umm Al–Naml, Kubbar, Qaruh, and Umm Al–Maradim. Bubiyan, the second-largest of the Arabian Gulf Islands, is composed of deltaic deposits from the Tigris and Euphrates river system. Failaka, lying 20 km northeast of Kuwait City at the mouth of Kuwait Bay, is thought by some to be the northernmost point of the Bronze Age civilization of Dilmun. There is also evidence that Failaka, referred to at the time as Ikaros, was settled by Greeks over 2,000 years ago. The total population of Kuwait in 2009 was 3,484,881, of which only 1,118,911 were Kuwaiti; the rest were foreign (The Public Authority For Civil Information, 2010). The weather is extremely hot in the summer and cold in the winter. The surface water drainage network is limited due to the arid climate and horizontal topography of Kuwait. Small wadis have been developed in the shallow depressions in the desert terrain. They flow intermittently after intense rains. Kuwait depends mainly on crude oil reserves of about 104 billion barrels—about 8% of world reserves. Its gross domestic product (GDP) purchasing power is $151.3 billion, while the per-capita GDP is

$54,260. The labor force is 2.091 million, with non-Kuwaitis making up about 60% of the labor force (Public Authority For Civil Information, 2008).

Kuwait is an arid country characterized by high temperature, low humidity, and high evaporation. It has no surface water and only a small reserve of fresh groundwater in north. The summers in Kuwait are intensely hot and dry, with daily mean highs ranging from 40°C to 46°C, and the highest recorded temperature of 51.5°C. From September to December, the temperature drops dramatically. In January, the coldest month, daytime temperatures range from 10°C to 30°C, falling to below 5°C at night, and on rare occasions dropping below freezing. The mean temperature does not exceed 20°C during the period from November to March. The mean temperature during the summer months is around 30°C. The annual mean temperature is 26°C. The temperature of the sea is 20.5°C in January and 31°C in July. The skies are usually clear over the country, and Kuwait averages nine hours of sunshine a day. Annual rainfall in Kuwait usually varies from 75 to 200 mm, with mean annual rainfall of 145 mm. Winters can be rainy, but most rain falls in the spring, from February to May. The volume of rainfall is 2.6 billion m^3, of which 160 million m^3 recharge the aquifer. Most of the rainfall evaporates under the extremely high temperatures. The mean annual potential evaporation is 4,000 mm. The mean humidity during wet season usually exceeds 70%, and it does not drop below 35% during the rest of the year. In August and September, humidity often reaches 100%. The atmospheric pressure oscillates around 1,020 mb during winter and 1,000 mb during summer. Kuwait has four main seasons and several sub-seasons. There are times of distinct weather, such as dust storms, thunderstorms, and persistent winds. Winter is the wettest and coldest season in Kuwait, characterized by northwest winds. Southeasterly winds may bring rain and an occasional dust storm. During spring, southeasterly winds, *suhaili*, bring hot air, and the *sarrayat* (local thunderstorm) is common (Parsons, 1963). Summer winds are variable, blowing from the northeast, northwest, and southeast, with almost cloudless skies. Sandstorms and very hot northwesterly winds in June and July increase the effects of the summer heat. In the autumn, winds switch from the southeast to the northwest in November and blow in any direction for several days (Food and Agriculture Organization, 2009)

Kuwait is one of the countries in the world without surface water. Its water resources can be classified into three significant categories: one natural resource, (1) groundwater, and two artificial resources, (2) desalinated seawater and (3) treated wastewater. In the absence of surface water, groundwater constitutes the most important natural water resource in Kuwait with Total Dissolved Solids (TDS) ≤ 10,000 mg/L in the central and southern areas of Kuwait. Only in the north can one find freshwater lenses in two groundwater fields, called the Rawdatain and Umm AlAish fields. Rawdatain Bottling Company produces 50,000 m^3 annually from the Rawdatain field. Brackish groundwater is used for irrigation, landscaping, construction work, nonpotable use in households, and mixing with desalinated water, up to 10%, to make it potable. The occurrence of usable groundwater is limited to the Kuwait Group and Dammam Formation aquifers, with salinity ranging between 2,500 and 10,000 mg/L. The percentage of groundwater from the available water budget is 32% with the possibility to increase the use of groundwater. The brackish water of the country is 15,000 to 20,000 years old and was developed during the wetter periods at that time. The general hydraulic gradient is from the southwest to the northeast, and the transmissivity ranges from 10 m^2/day to 1,000 m^2/d for the Kuwait Group, while for the Dammam aquifers it ranges from 50 m^2/d to 2,500 m^2/d (Al-Otaibi and Mukhopadhyay, 2005).

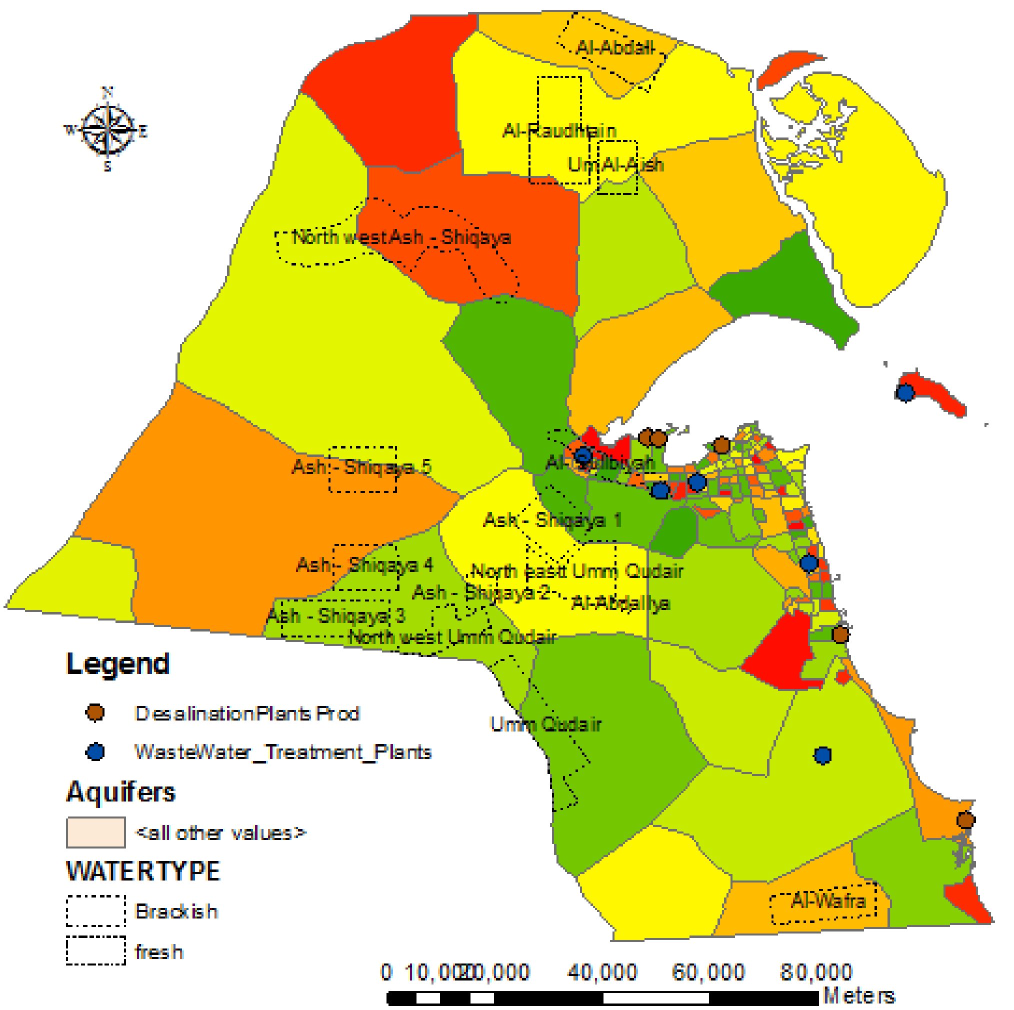


Figure 1 Location of groundwater fields, desalination, and wastewater treatment plants (AlRukaibi and McKinney, 2010)

2.1. Water Availability and Demand

Kuwait has limited water resources represented by small reserves of fresh groundwater and has to rely on several artificial water resources, such as desalination plants and wastewater plants to secure its water requirements for both potable and nonpotable water. Kuwait has depended almost entirely on desalination plants since 1953 for its drinkable water supply to domestic consumers. The first desalination plant was built with a capacity of 4,550 m^3/d in Shuwaikh (MEW, 2006). Kuwait's government has had to expand seawater desalination capacity to meet the increasing demand over the years. In addition, there is a great and increasing potential for the use of treated wastewater for such uses as irrigation and developing green lands. Kuwait is one of the global leaders in wastewater treatment. Brackish groundwater has been utilized since 1960 to supply consumers through a separate pipe network for use in landscaping, irrigation, construction work, and nonpotable use in households. Also, it is mixed with desalinated water, up to 10%, to make it potable. Kuwait is classified as one of the most water-scarce countries in terms of water availability (UN World Water, 2003). The current rates of water consumption are very high, with 459.6 L/C/d and 91 L/C/d for fresh and brackish water, respectively (MEW, 2007). The budget of water resources in Kuwait, represented as percentages of needed water, is 59% from desalinated plants, 32% from groundwater, with the possibility to increase the use of this resource, and 9% from wastewater treatment plants (Fadlelmawla and Al-Otaibi, 2005).

2.2. Production from Desalination Plants

Before 1925, Kuwait relied mainly on rainfall found near the surface in shallow wells. But due to population growth, that limited source became insufficient to supply the growing demand. Kuwait turned to the Shaat AlArab (Tigris and Euphrates River) for fresh water supply brought by dhows, and a primitive stage and distribution network was established. The situation changed with the influx of oil wealth when the first oil shipment was effected in 1946. Kuwait was the first country in the world to use cogeneration power desalting plants (CPDPs) in 1953 and adopt the flash-type technique (MSF) in the gulf area in 1957. Indeed, before the end of the 1950s, the first desalination plant was operational and produced 4,550 m^3/d (MEW, 2005). Figure 2 shows the development of production of desalinated water from 1980 until 2005 and installed capacity of desalination plants (installed capacity: the maximum volume can produce per day), and Figure 3 shows the percentage of production for each desalination plant from total production in 2005. Sabiya Station was under construction in 2005. The purpose of constructs a new desalination to supply desalinated water for Alhareer City (the city of Silk in Sabiya) and lower the pressure from the old desalination plants in Kuwait. Shuwaikh Station is expected to raise the current capacity to 93,193 m^3/day, and it is also expected to add new distillation plants Reverse Osmosis technology with a capacity of 136,380 m^3/d to reach a total installed capacity of 2,295,731 m^3/d (MEW, 2005).

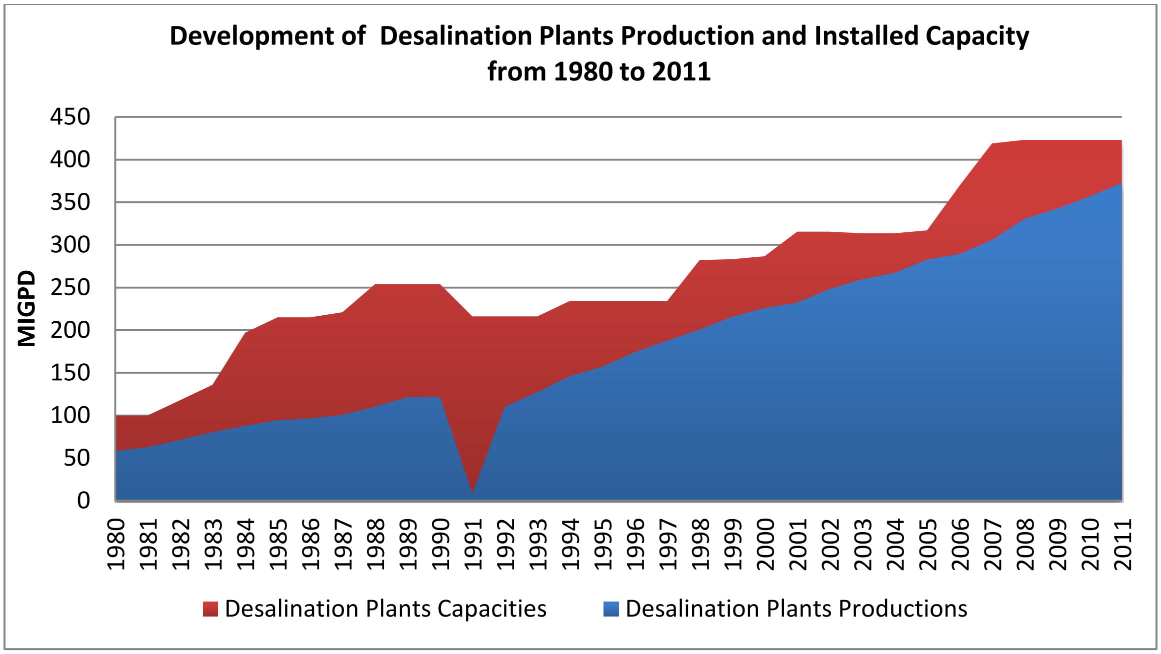


Figure 2 Developments of desalination plants and installed capacity (Source: MEW, 2012)

The production from desalination plants rises steeply year after year to meet the demands of the growing population, especially when desalinated water makes up more than half of the total water budget in Kuwait. Production reached 1.29 million m^3/day in 2005, a 25.2% increase from 2000. A new desalination plant called Sabiya plant was built north of Kuwait City. Sabiya Plant provided electricity and desalinated water in 2006 with the most advanced technological equipment and high capacity.

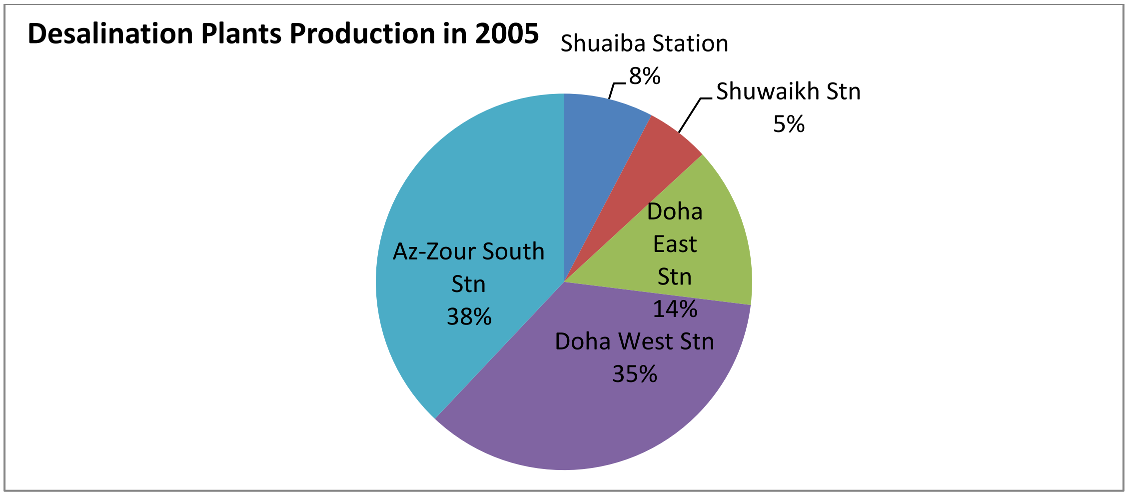


Figure 3 Desalination plants in 2005 to the production percentages (Source: MEW, 2006)

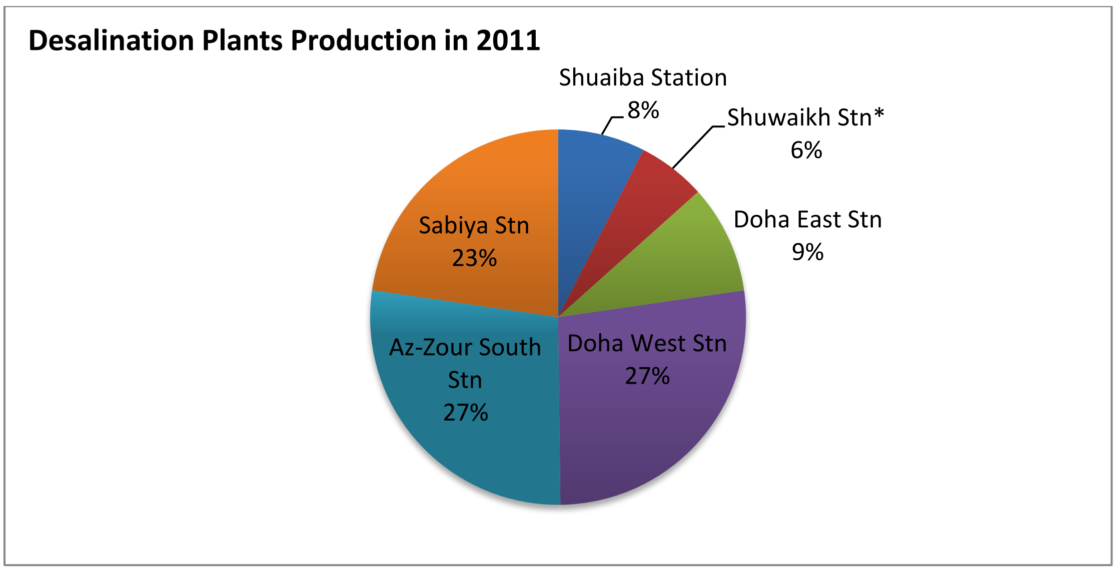


Figure 4 Desalination plants in 2011 to the production percentages (Source: MEW, 2012)

Figure 5 shows the development of freshwater production from 1980 to 2013, including net desalinated water plus brackish water required for blending. Figure 6 shows the average freshwater daily consumption between 2001 and 2005. The daily average freshwater consumption was high between May and October, exceeding 1.40 million m^3/day in 2005.

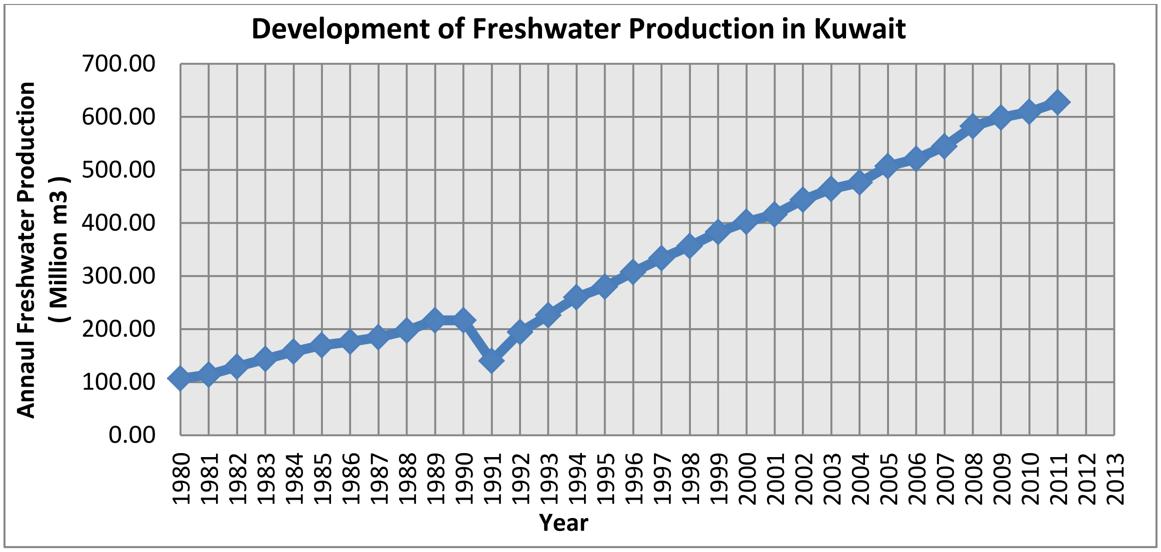


Figure 5 Production of freshwater supply in Kuwait between 1980 and 2011 (Source: MEW, 2012)

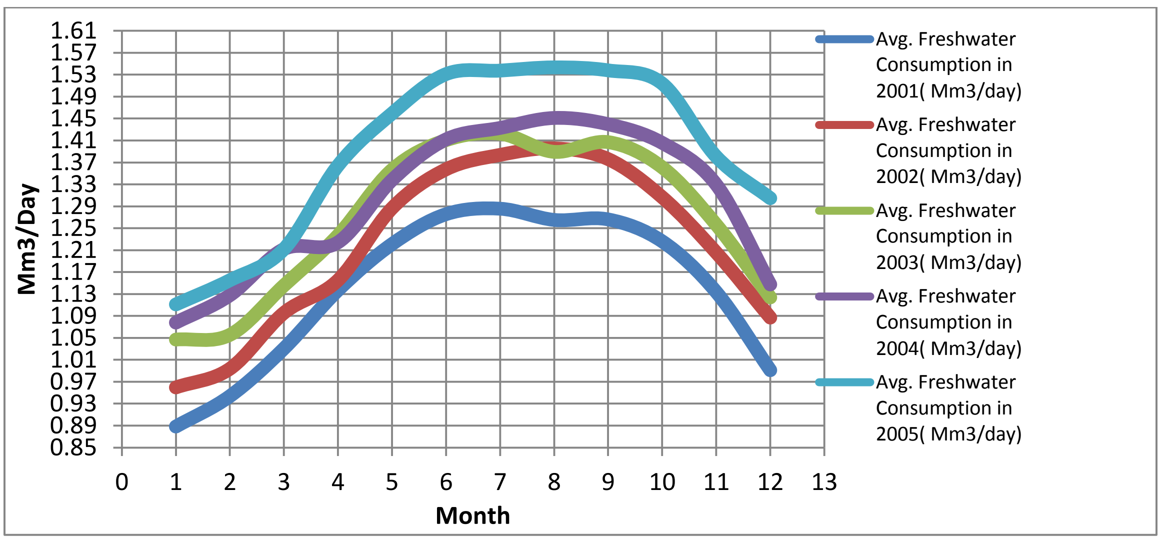


Figure 6 Averages freshwater consumption from 2001 to 2005 (Source: MEW, 2006)

The demand of freshwater increased after year 2000 as a consequence of the growing population; the consumption per capita increased to reach a maximum of 503.4 L/C/day in 2002 then dropped down to 459.6 L/C/day in 2007, with a total population of 3,238,035 (MEW, 2007).

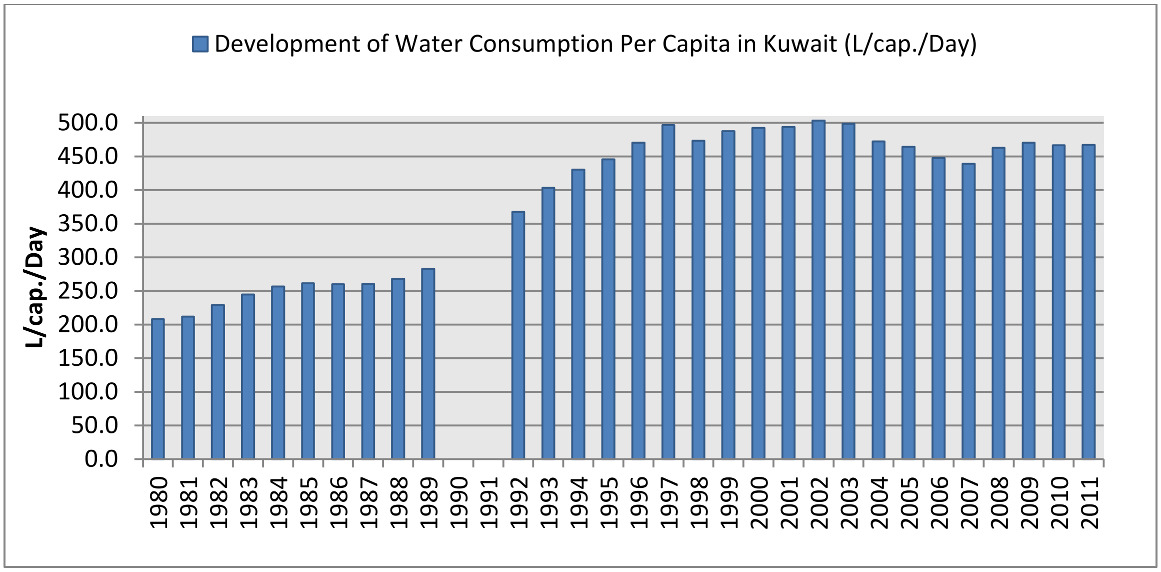


Figure 7 Freshwater consumption per capita in Kuwait between 1980 and 2011 (MEW, 2012)

2.3. Groundwater in Kuwait

Total consumption of groundwater with TDS between 2,500 and 5,000 mg/L in Kuwait has risen at a very fast rate over the past several decades. The production in 2007 was 146.90 million m^3/year, and the consumption in the same year was 108.38 million m^3/year. Table 1 illustrates the average daily consumption for each month from 2001 to 2005 (MEW, 2006). The current withdrawals of groundwater for farms located in the north (Abdally) and south (Wafra) of Kuwait are estimated to be 0.3–0.4 million m^3/day in each of the areas. The Minitry of Electricity and Water in Kuwait is responsible for supplying brackish water to residential consumers through its network.

Table 1 Annual and daily averages of groundwater consumption (Source: MEW, 2006)

	2001		2002		2003		2004		2005	
	Consumption (million m3/yr)	Daily Avg	Consumption (million m3/yr)	Daily Avg	Consumption (million m3/yr)	Daily Avg	Consumption (million m3/yr)	Daily Avg	Consumption (million m3/yr)	Daily Avg
Jan.	5.51	0.18	6.14	0.20	5.77	0.19	6.11	0.20	7.33	0.24
Feb.	5.45	0.19	5.99	0.21	6.13	0.22	6.89	0.25	6.70	0.24
Mar.	7.92	0.26	7.64	0.25	7.95	0.26	8.80	0.28	8.30	0.27
April	9.33	0.31	8.32	0.28	8.69	0.29	9.22	0.31	9.49	0.32
May	10.17	0.33	10.06	0.32	10.30	0.33	10.73	0.35	11.09	0.36
June	10.36	0.35	10.73	0.36	11.18	0.37	11.11	0.37	11.72	0.39
July	10.73	0.35	11.49	0.37	11.50	0.37	12.09	0.39	11.65	0.38
Aug.	11.18	0.36	11.18	0.36	11.79	0.38	12.95	0.42	11.60	0.37
Sep	10.79	0.36	10.69	0.36	11.53	0.38	11.88	0.40	10.90	0.36
Oct.	10.34	0.33	10.10	0.33	11.16	0.36	10.96	0.35	10.91	0.35
Nov.	8.54	0.28	8.19	0.27	8.98	0.30	9.30	0.31	8.96	0.30
Dec.	5.73	0.18	7.23	0.23	6.59	0.21	7.26	0.23	7.36	0.24
Total	106.05	0.28	107.75	0.32	111.54	0.31	117.30	0.32	116.0	0.32

2.3.1. Treated Wastewater

Using water from wastewater treatment plants has become a common practice in many parts of the world. Treated wastewater could be used for aquifer recharge in Kuwait. Mukhopadhyay et al. (2004) and Al-Otaibi (1997) concluded that treated wastewater is compatible for use in artificial groundwater recharge and recovery for both main aquifers in Kuwait. It is more logical to use treated wastewater that has a TDS value almost the same as that produced from desalination plants for a country like Kuwait, where natural water resources almost do not exist and the cost of desalting seawater is extremely high. In Kuwait there are four wastewater treatment plants that had a total capacity of 657,000 m^3/day in 2004, and about 30% of this was used for irrigation and developing green lands, while the rest was spilled to the sea. The last wastewater treatment plant, Sulibiya, was commissioned in 2004. It uses a reverse-osmosis system with an initial production of 0.32 million m^3/day. Table 2 shows the total volume that produce as treated wastewater from wastewater plants. It is planned for use to treat wastewater for artificial recharge of aquifers and recreational purposes such as artificial lakes and rivers.

Table 2 Production of treated wastewater in Kuwait

Wastewater Plants	Production in 2004 (Thousand m^3/Day)	Projection of Production in 2015 (Thousand m^3/Day)
Ardiya	337	635.6
Riqqa		
Jahra		
Sulibia RO	320	643
TOTAL	657	1278.6

2.4. Surface and Subsurface Storage

Surface storage in Kuwait is used for emergency conditions such as when desalination plants shut down or demand exceeds supply. The available freshwater storage capacity was 11.7 million m^3/day in 2006, including ground storage and towers storage (MEW, 2007). The demand in that year was 1.42 million m^3/day, which the stored water could supply in normal conditions for almost one week. This was not enough time to maintain and bring the desalination plants on line. Increasing the capacity of surface storage facilities to supply water in emergency conditions for longer times is very expensive. A study provided from Ministry of Electricity and Water compared the total cost of surface storage, desalination plants and aquifer storage and recovery to supply 45,469 m^3/day. The total cost for surface storage was $1.442 billion, while to construct a new desalination plant costs $103.5 million plus an operating cost of $7 million. Using the aquifer as subsurface storage cost $25 million, which is lower cost and does not require a vast area. The ASR system is considered to be a sustainable groundwater tool that can help and improve subsurface water. The aquifer can store huge quantities of water, more than surface storage is capable of storing without losses from evaporation. The storage is a complementary source when demand exceeds supply in dry times. Nevertheless, evaporation from surface storage results in large losses of water during the year, which may contribute to water shortages in times of water scarcity. Surface storage (reservoirs and tanks) is more vulnerable to the risk of contamination (due to direct contact to industrial pollution sources) and sabotage. On the other hand, the ASR system is safer and offers more protection from tampering. ASR systems are considered to be more environmentally friendly than surface storage systems. Enormous investment is required to construct surface storage, and a vast area is required to build such a system. In contrast, subsurface storage requires less cost, and land requirements are minimal (an acre or two per well). Figure 8 shows the increase in the capacity of surface storage with the number of tower storage systems.

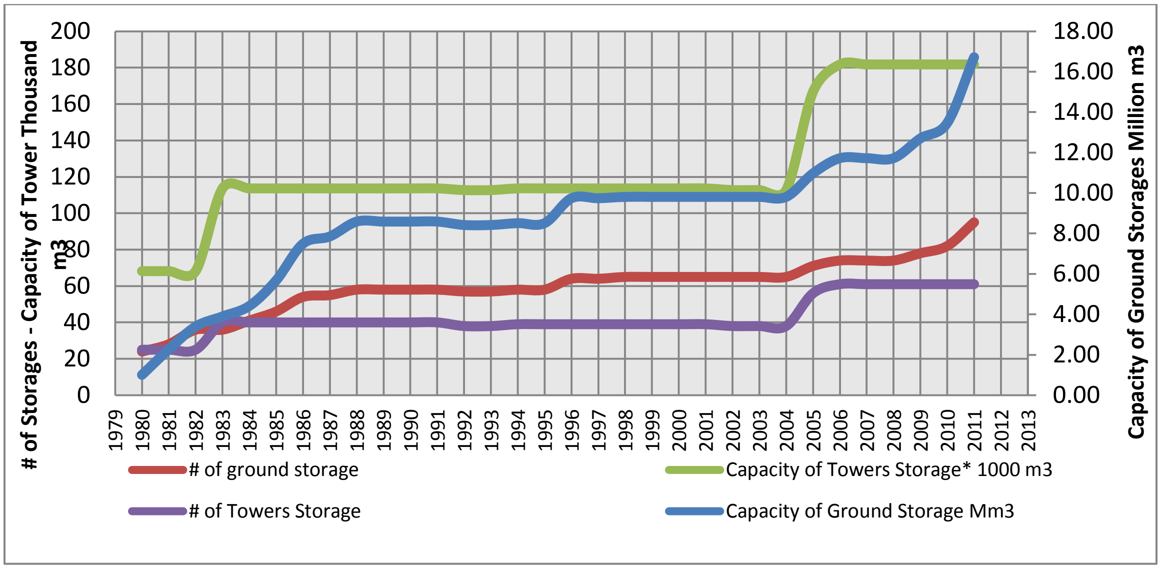


Figure 8 Capacity of ground storages and towrs storages (Source: MEW, 2012)

The next chapter discusses previous studies in the sustainable development field and considers an accurate definition that can cover all of its aspects. Also, the experiences of global organizations and researchers are explored that have initiated indicators in economic, environmental, and social fields from many reports published on the topic of sustainable development, indicators, and indices. Many authors have provided scenario techniques to analyze and evaluate water-distribution networks. Water pricing is a technique of water demand management policy that can be used to maintain and conserve the water system. Many authors in the United States, Europe, and the Middle East have developed provided water demand models to determine consumption based on water price and these are discussed in following chapter.

CHAPTER 3: Literature Review

Previous studies are the basis for this research work and for developing the proposed tools and techniques. A starting point for developing the desired approach is to review and adopt the existing knowledge that has a similar paradigm. This research deals with sustainability concepts and water infrastructure methods and will merge them by applying sustainable development to a case study to improve a water system. The four components discussed in this literature review are the concept of sustainability, water-distribution networks, sustainability indicators, and water price policy. All of them are important to initiating the drivers of Sustainable Water System and Infrastructure of Kuwait tool (SWSIK). A new water price policy in Kuwait is important due to the high demand in water consumption and to reduce the burning of fossil fuels required producing water from desalination plants.

3.1. Sustainability

Different authors and engineering organizations have published definitions of sustainability, but the most progressive comes from Brundtland (1987) in her definition of sustainable development (SD). She established the World Commission on Environment and Development (WCED) to pursue sustainable development pathways for all countries together. In the Brundtland Report ("Our Common Future"), her vision of sustainability is development that meets the demands of the present without compromising the ability of future generations to meet their own demands. She suggests that technology and social organizations can be both managed and improved to achieve sustainable development for a city.

Milman and Short (2008) agreed that there is no specific definition for sustainability, but any development using the concept of sustainability should integrate environmental and socioeconomic aspects together. On the other hand, Mori and Christodoulou (2012) discussed the comparison between weak and strong sustainability in terms of their functions. They also defined the conditions and assessments for city sustainability.

3.2. Sustainability Assessment and Indicators

Sustainable development requires a system of indicators to characterize progress toward sustainability. The World Bank Environment Department issued a report (Segnestam, 2002) that defined the conceptual aspect and theories of indicator frameworks of sustainable development. Three types of framework were discussed in the report: (1) an input-output-outcome-impact framework; (2) a framework developed by the Organization for Economic Co-operation and Development (OECD), such as Pressure-State-Response (PSR), and three different development directions frameworks that derive from PSR; and (3) a framework based on the theme of sustainable development. Starting with the framework developed by OECD in 1994, full details and examples were given for all framework versions; the basic version was called Pressure-State-Response (PSR), then driving force was added instead of the pressure indicator (DSR), the second variation was the Pressure-State-Impact-Response (PSIR) framework, and the last version was a comprehensive framework called Driving Force- State- Impact-Response (DPSIR) that analyses and assesses the situation by these factors (OECD, 2000a). This approach provided a practical framework and examples for different issues and analytical levels. There was also a set of criteria to follow to select the appropriate indicators to enable users to create and develop an accurate sustainable framework. Segnestam mentioned that time scale should be considered in the input data for indicators because it gives a predictable warning for the measured situation. At the end, she explained the tools that can be used for presentation and analysis of the indicator framework at the local, regional, and national scales.

Singh et al. (2009) presented sustainable development (SD) framework methodologies that considered the economy, environment, society, and technology institutional fields. The authors explained 70 types of indicator frameworks in depth to measure sustainable development. Normalization, weighting, and aggregation were three central steps in the methodology used by the authors to categorize indicator frameworks.

The water poverty index (WPI) is one of the integrated tools developed to measure water stress and water needs. Sullivan et al. (2006) developed the WPI and applied it at the community, catchment, district, and national levels. They mentioned that policymakers and sustainable water researchers should increase their participation in developing countries because only 12% of total aid had been given to the water sector for those countries in 2000–2001 (OECD, 2004). They developed the WPI to be a powerful tool that can characterize a region that has water issues in terms of supply, demand, and environmental impact. They explained the advantages of the WPI in relation to three points. It is an easy tool for decision makers in the water field to use and not as complex as other water indices. It has high potential and strength to provide accurate results for local communities. Finally, it has the ability to adjust the parameters of the index to apply to different spatial scales. The structure of the WPI is based on resources, access, capacity, use, and environmental components. A resource parameter (R_i) is evaluated for surface water and ground water availability, quantitative and qualitative assessment of its reliability, and water quality. The access (A_i) component measures the access consumers have to clean water and sanitation, considering water conflicts that cause disruption, the time required to deliver water from sources to consumers, and access to water deliveries for irrigation fields. The third parameter, capacity (C_i), is the social factor, which includes mortality rate for children under 5 years of age, educational level, membership in water-user associations, illness percentage from water, and the percentage of households receiving wages. In addition, the water-use parameter (U_i) measures the domestic water-consumption rate, agricultural rate, and livestock and industrial water use. Finally, the environmental (E_i) parameter indicates the use of natural resources, crop loss during critical periods of time, and ecological impact. Sullivan et al. (2006) assigned weighting coefficients to these parameters to stress which of them are more significant than others. They preferred weighting coefficients to have the same value to simplify the measurement and comparison between cases. The WPI is expressed as:

$$WPI = \frac{w_r\,R + w_a\,A + w_c\,C + w_u\,U + w_e\,E}{w_r + w_a + w_c + w_u + w_e}$$

The Policy Research Initiative (PRI) in Canada (2006) has developed a sophisticated index for monitoring, evaluating, and showing the progress of sustainability in terms of fresh water. The Canadian Water Sustainability Index (CWSI) comprises 15 indicators categorized by five components. The CWSI value is a total average score of five components:

$$CWSI = \frac{\sum_{i=1}^{N} w_i \, X_i}{\sum_{i=1}^{N} w_i}$$

Where X refers to the component *i* of the index, and *w* is the weight applied to the component. The components considered include resources, ecosystem, health, infrastructure, human health, and capacity (Table 2). The purpose of CWSI index is to identify the indicators that are close to or far from sustainability status and help decision makers understand which indicators they should consider improving.

Sandoval-Solis et al. (2011) proposed an index for sustainable water resource management. Reliability, resilience, and vulnerability were the performance indicators for measuring the sustainability for either water users or basins. The objectives of the sustainability index for water resources were to analyze and compare water management policies with respect to sustainability at the national scale and illustrate trends of sustainability and progress at the local scale. They improved the sustainability index proposed by Loucks (1997) by reflecting the sustainability of each group of water users.

Table 3 CWSI indicators (SOURCE:PRI, 2006)

	Component	Indicator	Description
Canadian Water Sustainability Index	Resource	Availability	The amount of renewable freshwater that is available per person
		Supply	The vulnerability of the supply as caused by seasonal variations and/or depleting groundwater resources
		Demand	The level of demand for water use based on water license allocations.
	Ecosystem Health	Stress	The amount of water that is removed from the ecosystem
		Quality	The Water Quality Index score for the protection of aquatic life
		Native Fish	Population trends for economically and culturally significant fish species
	Infrastructure	Demand	How long before the capacity of water and wastewater services will be exceeded due to population growth
		Condition	The physical condition of water mains and sewers as reflected by system losses
		Treatment	The level of wastewater treatment
	Human Health	Access	The amount of potable water that is accessible per person
		Reliability	The number of service disruption days per person
		Impact	The number of waterborne illness incidences
	Capacity	Financial	The financial capacity of the community to manage water resources and respond to local challenges
		Education	The human capacity of the community to manage water resources and address local water issues
		Training	The level of training that water and wastewater operators have received.

Milman and Short (2008) proposed a new indicator called water provision resilience (WPR) that measures the resilience in water systems with respect to sustainability. They explained the basic components of the WPR and the factors that play important roles with respect to access to water for the population. The purpose of this paper was to make a bridge between water supply for the population and access to safe water, where indicators can provide an early warning of weak areas that need improvements to water system resilience.

In this research, the indicators of Sustainable Kuwait Index (SKI) were composed of past works of sustainability indicators and especially related to improving water systems. Indicators of Canadian Water Sustainability Index (CWSI) were adapted and adjusted to comply with the water system in Kuwait. In addition, some indicators from past studies provided the approaches to determining sustainable indicators.

3.3. Water Distribution Network (WDN)

Moving water from the source to the customer requires a water infrastructure that includes water plants, storage, pipelines, valves, pumps, appurtenances, and demand nodes. All of these components are sensitive to failure of water delivery, distribution, and maintenance. The Water Distribution Network (WDN) is a comprehensive topic covering network analysis in terms of reliability, vulnerability, connectivity, rehabilitation, and performance under different variable situations such as climate change.

Singh et al. (2007) present risk and reliability analysis. The reliability technique of WDN analysis is defined as the capability of the network to deliver water at demand nodes in terms of total water available and pressure heads. They defined two types of reliability of WDNs, mechanical and hydraulic reliability. They derived an adjusted supply equation for when theoretical supply is less than actual demand, which happens due to underestimation at the time of planning or demand growth due to population increase. They provided examples to measure the reliability of networks in case supply is above or below demand.

$$Q_{supplied} = \frac{Head - Head_{min}}{H_{Service} - Head_{min}} * Q_{theoretical\ required}.$$

Wu et al. (1993), Lu et al. (1999), and Agarwal et al. (2001a) proposed structure vulnerability theory (SVT) for engineering systems. They considered SVT a concept that is applicable to all systems, whether technical or social. They developed the theory to analyze the consequences that lead to vulnerable failure scenarios. Overall, they tested all possible actions that lead to risks to the system by SVT. Their theory was the basis for further research on the WDN. They introduced the concept of vulnerability in WDNs.

Pinto et al. (2010) brought new terminology to water infrastructure analysis that is based on SVT, called the Theory of Vulnerability of Water Pipe Network (TVWPN). Their approach was to empower the water pipe network to be stronger against failure. The main objective of TVWPN is to identify the vulnerable parts of water infrastructure based on (1) clustering and (2) unzipping processes. In the middle of two these processes, a hierarchical model is built representing the WDN. Finally, they defined a vulnerability index that represents the ratio of separateness (the percentage of head loss in the WDN) to the relative damage demand (maximum allowable pressure for pipes) for a specific failure situation. Also, Pinto et al. (2010) applied TVWPN to oil and gas pipeline distribution network design, providing guidelines for assessment, measurement, and analysis of oil and gas distribution networks in order to reach efficient levels of operation.

Duarte et al. (2012) evaluated the risk in a water pipe network after applying TVWPN to several cases. They estimated the risk of failure that is the chance of complete failure or its consequences. They proposed examples of WPN design to achieve system robustness. They concluded that TVWPN can be applied to any system to provide measurement of failure consequences and risk associated to WDN.

Bentes et al. (2011) reinforced the TVWPN method by analyzing three water networks and discussing the reliability, vulnerability, and resiliency of each system. They gave high consideration to what happens after the unzipping process, or the process of searching for the pipeline that fails to supply or is damaged. This is called a risk failure scenario in WPN. They described TVWPN as a good water-infrastructure tool to address the redundancy of WDNs. Ostfeld (2005) defined the water distribution system as a graph with points (source and demand node) connected to each other by lines (pipelines). His methodology provided a backup digraph and one-level system redundancy for WDNs. System connectivity and topology analysis was used to develop the backup scenario by applying it to two cases.

SWSIK tool is a tool to analyze water systems and infrastructure. Previous work in WDN analysis has contributed to shaping the approach of the SWSIK tool to analyze the critical components of WDN. Additionally, the SWSIK tool is continuing to follow the theoretical concept of TVWPN to identify failure scenarios in WDN by being applied to Kuwait water infrastructure.

3.4. Water Price Policy

The integrated urban water management tool has two approaches: water and non-water price policies. Integrated urban water management has been shown to be an efficient tool to control and maintain water consumption. Many studies discussed in this section have proved that water price policy has a high impact on reducing water consumption when applied on a reasonable scale. Most previous studies have found that there is a relationship between price elasticity and the variables of household size, household income, household education, water price, climate, and conservation campaign and propaganda. Renwick and Green (1999) assessed California water agencies and the role of water and non-water price policies to reduce water consumption. The performance of water price and demand-side management (DSM) policies were implemented in a residential area in California between 1989 and 1996 to reduce water demand. Eight agencies participated in collecting data. A different pricing schedule and DSM were used in each of the eight urban agencies. The marginal water prices varied from \$0.17 per m3 to \$1.33 per m3, while all eight agencies used at least one type of DSM policy to reduce household water demand in an efficient manner. INFO, RETRO, REBATE, RATION, RESTRICT, COMPL are non-price demand side management policy (DSM). These types of DSM were used as parameters in demand equation to analyze their performance in reducing water demand in California. Two parameters consider outdoor water usage which (LIRR) parameter for Limited outdoor water use and HIRR3 parameter for high outdoor water use As a result, they provided a residential water demand model that can estimate monthly water demand per household (W) based on the variables of water price (MP), difference variable (D), household income (INC), family size (LOT), average maximum temperature (TEMP), precipitation (PREC), and DSM policies implemented during the study.

$$\text{In } W = \beta_o + \beta_1 \text{ In MP} + \beta_2 \text{ In D} + \beta_3 \text{ In INC} + \beta_4 \text{ INFO} + \beta_5 \text{ RETRO} + \beta_6 \text{ REBATE} + \beta_7 \text{ RATION} + \beta_8 \text{ RESTRICT} + \beta_9 \text{ COMPLY} + \beta_{10} \text{ LIRR} + \beta_{11} \text{ HIRR3} + \beta_{12} \text{ In TEMP} + \beta_{13} \text{ In PREC} + \beta_{14} \text{ LOT}$$

This model allows policymakers to choose among all input variables to implement the model in a specific region. Overall, the model can provide 5–15% reduction in water demand with a modest water price and at least one type of DSM. They encouraged policymakers to increase water price to obtain more than a 15% reduction in demand.

Dandy et al. (1997) focused on studying the impact of water price rate structure followed by a certain free allowance of freshwater for household consumption. Their model analyzed two categories: below and above the free allowance. They tested the water demand model on data for Adelaide in South Australia to estimate the annual water consumption per household. Their model was based on a linear form applied on an annual time scale. They came up with a new water price structure with two components: first, it allows consumers an amount of freshwater free of charge; then, water is priced by rate structure when in excess of the free allowance. Their equations determined water demand (Q) in cases below or above the free allowance (A) assigned by policymakers. The input data for the following equations are explained in table 4.

<u>Q <A:</u> $Q = \alpha_0 + \alpha_1 Q_{-1} + \beta_1 I + BZ + \theta D_y + BZ + u$

<u>Q >A:</u> $Q = (\alpha_0 + \delta_0) + (\alpha_1 + \delta_1) Q_{-1} + (\beta_1 + \gamma_1) I + (B + \Gamma) Z + \theta D_y + \Phi P + u.$

Price elasticity is the change in water usage per unit price. The impact of water pricing on residential water usage is inelastic. But price elasticity value gives the sensitivity of water use to percent change in water price. They found price elasticity in the range of -0.6 to -0.8. The property value (income) and household size factors are important to compute water demand based on their results. They confirmed that the consumption (Q) above the allowance (A) is more sensitive to income and climate variables than consumption below the allowance. Overall, the Australian water demand model can determine consumption based on the free allowance technique.

Table 4 Input for Australian Water demand Model

Term	Description	Unit
Q	Water consumed	1000 L / year
Q_{-1}	Water consumed in previous year	1000 L
A	Annual allowance	1000 L / year
D_y	Value for year 1992	-
I	Property Value (wealth, Income)	$
P	A vector for Price Variable (P_M, P_B)	$/ 100L
Z	A vector of other variables (household size, climate, etc.)	-
α β δ θ	Coefficients	-
Β Γ Φ	Vectors of coefficient	-
u	Error Term	-

Abu-Rizaiza (1991) proposed several models for estimating the residential water usage for different kinds of water users. He developed a model based on socioeconomic and climatological data of major cities in the Kingdom of Saudi Arabia (KSA). The model contains the following variables; income (INC), family size (FSIZE), temperature (TEMP), whether the house has a garden (GRDN), and water price (PRIC). He conducted a survey to determine the water demand function. He tried to find the relationship between water demand and the input variables mentioned above. The water-demand model determined monthly water usage per household (Q) from the following equation:

$$\text{Log (Q)} = \alpha_0 + \alpha_1 \text{ Log (INC)} + \alpha_2 \text{ Log (PRIC)} + \alpha_3 \text{ Log (FSIZE)} + \alpha_4 \text{ Log (TEMP)} + \alpha_5 .\text{ GRDN}$$

At that time, water price in KSA was based on a block pricing method; the first block (100 m^3) costs \$0.08 per block, water usage between 101 and 200 m^3 is the second block and costs \$0.267 per block, the third block is water usage between 201 and 300 m^3 and costs \$0.533, and water usage above 300 m^3 cost \$1.067 per block. The average water consumption was 350 L/capita/day, and average family size was six persons per household. He used SAS software to estimate coefficients to fit the best possible set. His model showed a positive relationship between all input variables except water price. The price elasticity was found between -0.78 and - 0.06. His study was the baseline for further water price research in the GCC's countries region.

Ayadi et al. (2002) conducted a study to determine water demand based on different brackets of water consumers in Tunisia. They classified consumers into upper and lower brackets based on consumption level. Consumption level was provided by the National Water Distribution Company (SONEDE). The following equation is the function of income (R), water price (P), network size (N), rainfall (RL), and dummy factors (QD) to determine the monthly water demand per household (C):

$$\text{Log (C)} = \alpha_0 + \alpha_1 \text{ Log (R)} + \alpha_2 \text{ Log (P)} + \alpha_3 \text{ Log (N)} + \alpha_4 \text{ Log (RL)} + \sum \alpha_5 .\text{QD}$$

Ayadi et al. believed water consumption in Tunisia was affected by water prices in the upper bracket, which has economic activity and alternative sources of supply. They suggested increasing water prices for the upper bracket due to higher elasticity (-0.4). There would be no benefit of increasing water prices for the lower bracket because of the small value of elasticity (-0.1). These results led them to confirm that a decentralized and effective pricing strategy can decrease water consumption.

Milutinovic (2006) proposed an adaptive model to determine water usage in Kuwait. It was the first study to propose a new water price system in Kuwait. He depended on previous studies in California, Spain, Australia, and Saudi Arabia to test alternative water price structures. He correlated income distribution and household size from U.S. data by using the GDP of Kuwait. The only known variable in their study was water consumption per capita in 2006. He proposed that an alternative water price structure be implemented in Kuwait, such as a constant price, a block pricing, and free allowance followed by a constant price. His results indicated that a water price of $1 per m^3 for water use over the free allowance given by the government would reduce water consumption by 40%. His study of the adaptive residential water-demand model was considered the baseline to reform water policy practice in this research. Using a real Kuwaiti data and the actual coefficients from the original models can develop this previous study.

The next chapter explores the methodologies used to achieve the objectives of promoting the sustainability of the water system and infrastructure in Kuwait. This research depends on three main activities of the research, which are the Model Urban City (MUC), sustainability vision, and water price policy scenarios.

CHAPTER 4: Methodology

4.1. The Basic Theory of the Research

The mechanism of this research depends on three main foundations. First, GIS data and hydraulic model integration are developed to provide a unique geodatabase in ArcGIS called Model Urban City (MUC). This geodatabase is used to initiate scenarios for current and upcoming growth situations of water systems in Kuwait by using the InfoWater GIS software application (Innovyze, 2011). Water distribution system models created in the InfoWater GIS framework are used to evaluate outputs to identify system pressure zones, vulnerability, and reliability.

The second main activity develops a sustainability index that empowers decision makers and researchers with knowledge of the trends of sustainability for each specific area and lets them characterize how close or far they are from a desired sustainability level. Indicators give a unique numeric value that simplifies complicated information and allows exploration of the deficits in each factor in order to reach the sustainability level. This index has been adopted and adjusted based on previous studies of creating indicators appropriate for the Kuwait water system framework. Environmental, economic, and social components are the three bottom lines of sustainability; they are used to create the Sustainable Kuwait Index (SKI) to measure the sustainability level. SKI contains 16 indicators that are classified into four subcategories, resources, infrastructure, capacity, and socioeconomic factors. Integrating the water distribution system allows the creation of a new analysis tool, the Sustainable Water System and Infrastructure of Kuwait (SWSIK) tool, that can identify socioeconomic issues and characterize the weaknesses in the water system and its infrastructure. SWSIK is a comprehensive analysis tool that defines the vulnerability, reliability, connectivity, and robustness of a water distribution system. Also, the SWSIK tool includes a water price variable scenario to generate economic and environmental results as a consequence of implementing that scenario. SWSIK evaluates a water system from a two-dimensional approach and provides the effective benefits for each approach. The first approach is analysis and evaluation of the consequences of water consumption due to different water price policies, while the second approach is identification of vulnerabilities in WDNs.

The last main activity develops a water-demand model to estimate residential water usage from previous studies. Then, a water system supply and demand curves is developed based on variables that change with the level of government subsidies in water prices. A water demand model for Kuwait was developed to estimate water consumption for different water price polices. To address water scarcity issues, better pricing has been recognized as an important tool. The previous studies highlight a large concern about improving pricing structure in order to move toward sustainable consumption. The main purpose of this research is to explore ways to reduce water overconsumption by integrating sustainable management and planning. The necessity to reform pricing systems is a main goal of integrating the water system and infrastructure. Three water price structure scenarios are evaluated to reduce water overconsumption. Then, the SWSIK tool is used to evaluate the economic, social, and environmental aspects for three scenarios. In addition, a measure of the influence of government subsidy was analyzed based on alternative water price scenarios to reduce both water consumption and fuel energy. Provide alternative scenarios to reform water price policy approach gives decision makers the ability to select the optimum option for government and consumers. Also, It helps them to predict when a new desalination plant is needed and how much fossil fuels will be consumes for the coming years. The SWSIK tool is applied to describe, predict, and control patterns of consumption and analyze critical infrastructure systems.

4.2. Activity 1 – Model Urban City

Water distribution networks (WDNs) are not as simple as other infrastructure systems, and the complexity of WDNs lies behind the interaction of a network's elements and hydraulic properties and specifications (Yazdani & Jeffery, 2011). A geodatabase of the Kuwait water system has been created to provide a detailed dataset that can be used to effectively evaluate water systems and their sustainability. In addition, the dataset can be imported into the ArcGIS InfoWater framework to use as input for simulating current and future scenarios. The WDNs of Kuwait were imported from AutoCAD format to Shapefile format to be used in ArcGIS. Transforming AutoCAD maps was a challenging procedure for which all the distribution network information was collected for multiple areas in one united map and then, based on the Projected Coordinate System (KTM); it was matched to the Kuwait base map. The next step was to develop the network topology, which was checked for connectivity between hydraulic elements (pipes, valves, pumps, tanks, and reservoirs) using ArcGIS Geometric Network tools. The three big "Ss" for WDNs are system structure, scenarios, and system boundaries, which are represented by the concept of the model urban city (Hellström et al., 2000). A geodatabase of the Kuwaiti water system was defined as a system structure that has hydraulic elements for both freshwater and brackish water distribution networks, infrastructure data, and demand tables that monitor the consumption for urban areas. The scenario component allows simulating standard scenarios over different time scales (past, current, and future cases) by Infowater application, including critical situations such as water shortages, consumption behavioral changes, and socioeconomic influence. The last component is system boundaries, including spatial dimension, time scale, water price, population, and temperature factors. The first activity of this research is the Model Urban City (MUC), an interacting framework inside ArcGIS. The three components of the MUC can provide a fast initial assessment and intermittent scenarios for analysis and evaluation using the SWSIK tool.

Figure 9 Model Urban City

4.2.1. InfoWater Software Application

The InfoWater software application is an ArcGIS-based solution (Innovyze, 2011). InfoWater gives a highly accurate view of the performance of WDNs. It integrates advanced water networks with simulation and optimization functionality. It can control supply and demand scenarios at an acceptable pressure and flow rate. InfoWater provides tools for browsing results in either tabular or graph formats with a report manager.

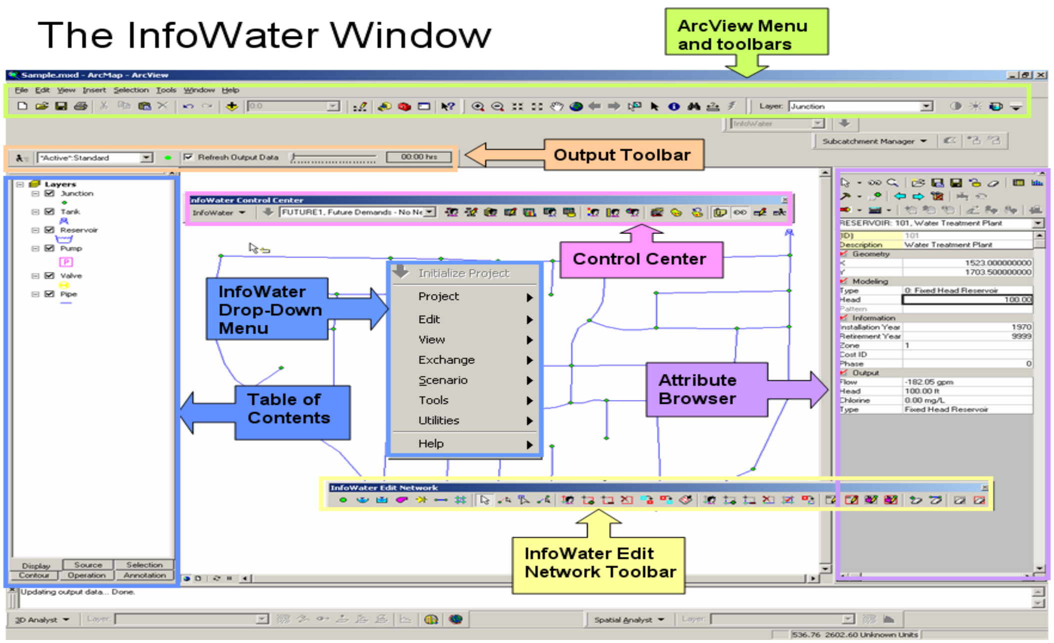


Figure 10 InfoWater Windows

4.2.2. Structure of Water System

The structure of the Kuwaiti water system in GIS has been classified into feature classes, demand tables, and raster layers for use in creating SKI and its indicators. Likewise, the elements of the structure represent input fields in the scenario component in MUC.

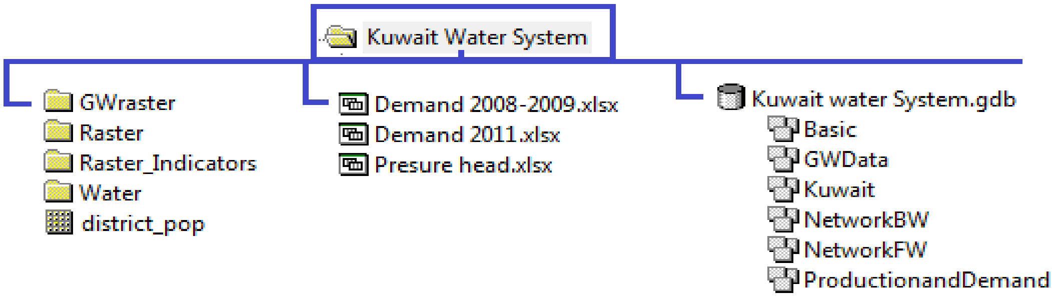


Figure 11 Structure of Kuwait Water System

4.2.3. Water System Scenarios

The second component of MUC is scenario analysis, where the real WDN is modeled using simulation and optimization. Many scenarios can be created for past, current, and future growth of the WDN inside InfoWater. InfoWater is capable of browsing both model input data and analysis results in a tabular format using the database editor tool. For instance, the demand setting has to be updated for each time interval using the demand table from the structure component in MUC. The rest of the datasets can be joined and related with the feature classes and tables that match each element. The relationship between the dataset in the scenario component and elements of the water system have the same data model as the ArcHydro framework data model (Maidment, 2002).

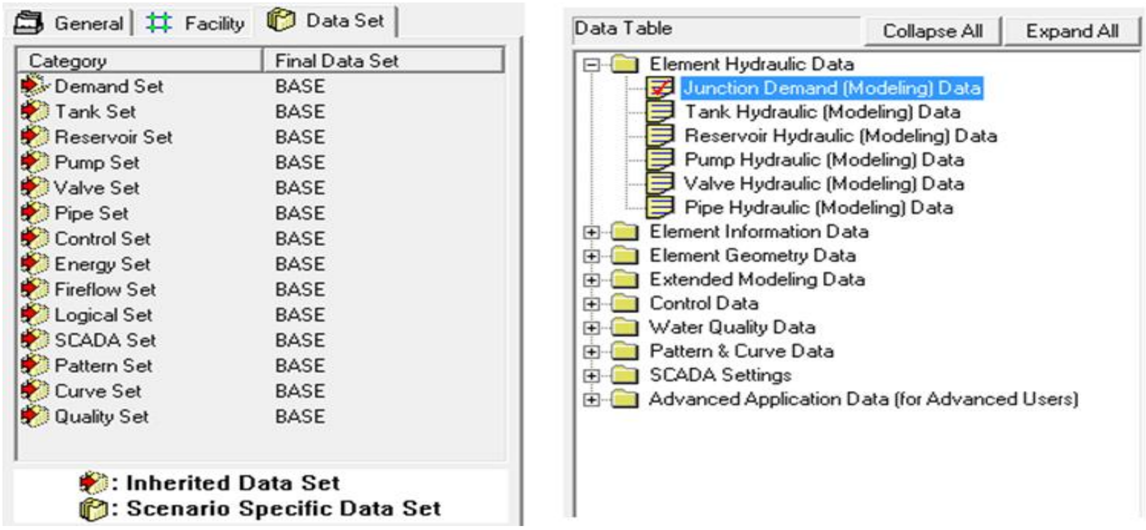


Figure 12 Data Set of InfoWater Application for water system scenarios

4.2.4. Water System Boundaries

Each engineering system has properties and specifications that define its boundaries and the factors that could change the current shape or function of the system. Similarly, system boundaries are represented by their spatial and temporal limitations, water consumption patterns, and influence factors (climate change, economic crisis, and population increase or decrease). To achieve the goal of the research, developing sustainable water systems considering both demand and supply factors, the spatial boundaries are the urban areas, while the time scale boundary is the monthly water demand for residential consumers. Each area has a raster catalog that is a multi-raster for monthly demand, total population, total water price, and total residential houses. The water consumption pattern (Figure 13) was developed based on both the regular hours that families consume water inside the house or work and a public survey that was published on social networks (Twitter, Facebook, and Instagram) especially to measure the awareness and behavior of Kuwaiti consumers regarding water.

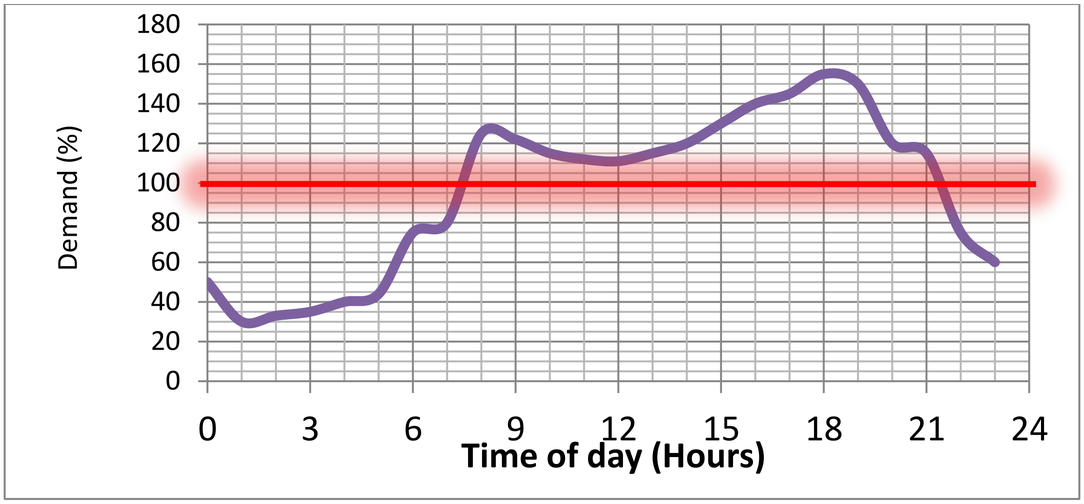


Figure 13 Water Consumption Pattern in Kuwait

4.3. Activity 2: Water System Sustainability Vision

The term *sustainability* has become the most frequent expression to determine the state of development of countries in three basic fields: economy, society, and environment. The vision of creating a sustainability framework is reached by managing, conserving, and improving the physical infrastructure interconnecting economic, social, and environmental aspects with solutions for current and future states. Sustainability in this research is focused on water systems and their associated factors. In order to reach the sustainable concept of a water system, one must understand and analyze water resource data (conventional and nonconventional), infrastructure, social behaviors, fossil fuel emissions, energy consumption, and economic patterns. Using the MUC as input, the objective of sustainability of the water system of Kuwait can be achieved with two main fundamental goals of the sustainability vision:

- Goal 1: Sustainable Kuwait Index (SKI)
- Goal 2: Sustainability of Water System and Infrastructure of Kuwait (SWSIK)

4.3.1. Sustainable Kuwait Index (SKI)

A sustainability index provides a simple number instead of complicated information for decision makers to use as a basis for sustainability assessment (Segnestam, 2002). This research initiated and created a group of indicators to represent the current state of the sustainability of the water system and its infrastructure. The sustainable Kuwait Index (SKI) is composed of a group of indicators in socioeconomic and environmental dimensions in terms of a water system (Figure 14). The objective of the SKI is to measure the trend of sustainability for each specific area and let each indicator characterizes how close or far it is from the sustainable level. Indicators are one technique for promoting sustainability that give unique numeric values that simplify complicated information and allow exploration of the deficits in each factor in order to reach a sustainable level.

The SKI contains 16 indicators that are classified into four subcategories related to resources, infrastructure, capacity, and socioeconomic factors. Depending on the scenario results, the sustainability indicators are synthesized to provide a holistic sustainability profile of the water system in Kuwait and indicate the percentage achievement of the level of sustainability in terms of the economic, social, and environmental aspects of the system. The SKI score is the average of the four sub-category scores. Each subcategory can be computed by dividing the sum of values of the indicators by the total number of indicators. The range of all indicators is between 0 and 100, where higher scores indicate higher sustainability for that indicator. Some of the indicator equations have been adopted and adjusted from previous studies that used a similar approach to measuring the sustainability of water systems. For other indicators, mathematical techniques have been used for the evaluation criteria, such as linear transformation, standardized score range transformation, and fuzzy logic transformation. The SKI attempts to support decisions related to water demand and supply management by illustrating the effectiveness of applying policies such as water price policy for water conservation or the need for new storage due to population growth. The benefits of applying a new water management policy can be judged positive if the SKI score is increased. The ideal sustainability level can be achieved by applying effective water management tools that consider improvements to the triple bottom line of sustainability. The overall goal of indicators in SKI is to monitor changes in the sustainability level in case significant factors are applied to reduce water consumption or increase water supply.

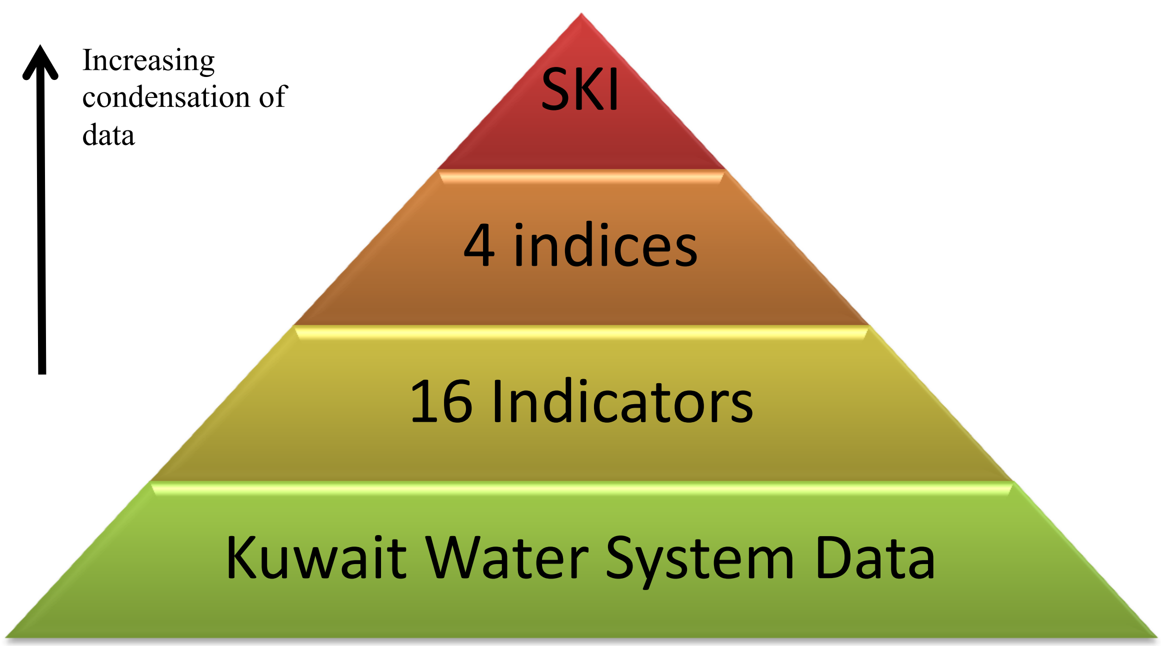


Figure 14 Sustainable Kuwait Index (SKI) Pyramid

4.3.1.1 SKI Indicators

The SKI is ultimately designed to measure the state of sustainability by 16 indicators that are classified into four subcategories. The SKI indicators aim to improve the sustainability of the water system in Kuwait by looking at local, national, and global standard values of sustainability.

(a) Environmental Category

This category contains indicators that are related to the resources, infrastructure, and capacity of water systems in Kuwait. The environmental category includes 12 indicators that measure the sustainability of water systems. A high score for an indicator means that it has potential to improve sustainability.

- **Resources**

  The availability, renewability, recharge, and demand indicators are components of the resources subcategory. Each of these indicators measures a significant aspect of the water system. The resources score is determined by taking the average score of the four indicators that make up this subcategory.

(1) Availability (R_{av})

This indicator measures the percentage of water production capacity remaining before the system reaches maximum production. It represents the ratio of water production to total installed capacity for desalination plants (equation 1). Linear transformation is used in this indicator to measure the sustainability of water availability.

R_{av} = [1 – (total supply per day/ total installed capacity per day)] * 100 (1)

(2) Renewability (R_r)

This indicator uses the Falkenmark (1974) water stress indicator compared to the amount of renewable freshwater resources per capita to determine the renewability score. The amount of renewable freshwater assigned by Falkenmark is 1,700 m^3/cap/year to meet water requirements. This indicator considers the renewable surface and groundwater flow of the whole country. The renewability indicator (R_r) is determined by equation 2. The renewability score is calculated based on a standardized score evaluation, which uses the renewable water resources per year per capita (T) as input (Policy Research Initiative, 2006).

$$R_r = \frac{T-500}{1700-500} * 100 \quad \text{[If T > 1700 then } R_r = 100\text{; if T < 500 then } R_r = 0] \qquad (2)$$

(3) Recharge (R_{ASR})

This indicator (R_{ASR}) represents the sustainable water supply, called aquifer storage and recovery (ASR). The recovery efficiency (RE) is the ratio of volume of water recovered with TDS less than 1,500 mg/L to the volume of water injected in ASR operations (Alrukaibi et al., 2010). This indicator used the recovery efficiency of ASR variable as a sustainable indicator.

$$R_{ASR} = [\frac{(\text{volume of water recovered with TDS less than 1500 mg/L})_{Cycle}}{(\text{volume of water injected})_{\text{Cycle}}}] * 100 \qquad (3)$$

(4) Demand (R_D)

This indicator (R_D) measures the condition of sustainable demand for an area. By looking at the daily water use per capita based on the standard approach of consumption per capita at the country scale ($D_{STD.}$), the demand indicator can be computed. The standard daily per capita water consumption is 250 L. It was assigned by the policymakers in MEW in Kuwait. The water per capita for area *i* is D_i (Di =Demand$_i$/Population$_i$) and represents the water consumption measured from water sensors built into pipelines serving this area (i). The demand indicator is 100 if D_i is less than D.

$$R_D = [D_{STD}./ D_i] * 100 \tag{4}$$

- **Infrastructure**

This subcategory evaluates the water infrastructure at the local (area) scale. It has four indicators, each of which examines the ability of the infrastructure to provide freshwater of appropriate quality and quantity. The indicators are dependent on the capacity of water storage tanks. The final simple index score for the subcategory is the average of the four indicator scores.

(1) Storage (I_S)

The storage indicator (I_S**)** Focuses on supply from surface reservoirs and elevated tanks. In case a desalination plant is shut down for some critical reason, the storage that is distributed over the country has to cover the water demand for each area. The indicator measures the days for which an area can survive with only water from storage. The types of water storage in Kuwait are surface reservoir and elevated tank. Equation 5 determines the storage indicator by dividing the number of days that the storage can supply the specific area by 30 days. The maximum time that is required to restore a desalination plant to working, based on data from the Ministry of Electricity and Water (Energy), is 30 days.

$$t_d = \left[\frac{(Reservoir\ volume\ for\ area)_i + (Tank\ volume\ for\ area)_i}{(water\ per\ capita\ for\ area * populatiom)_i}\right] \quad (5A)$$

$$I_s = \begin{cases} 100 & if\ t_d > 30\ days \\ [\frac{t_d}{30}] * 100 & if\ 0 < t_d \leq 30 \\ 0 & if\ t_d = 0 \end{cases} \quad (5B)$$

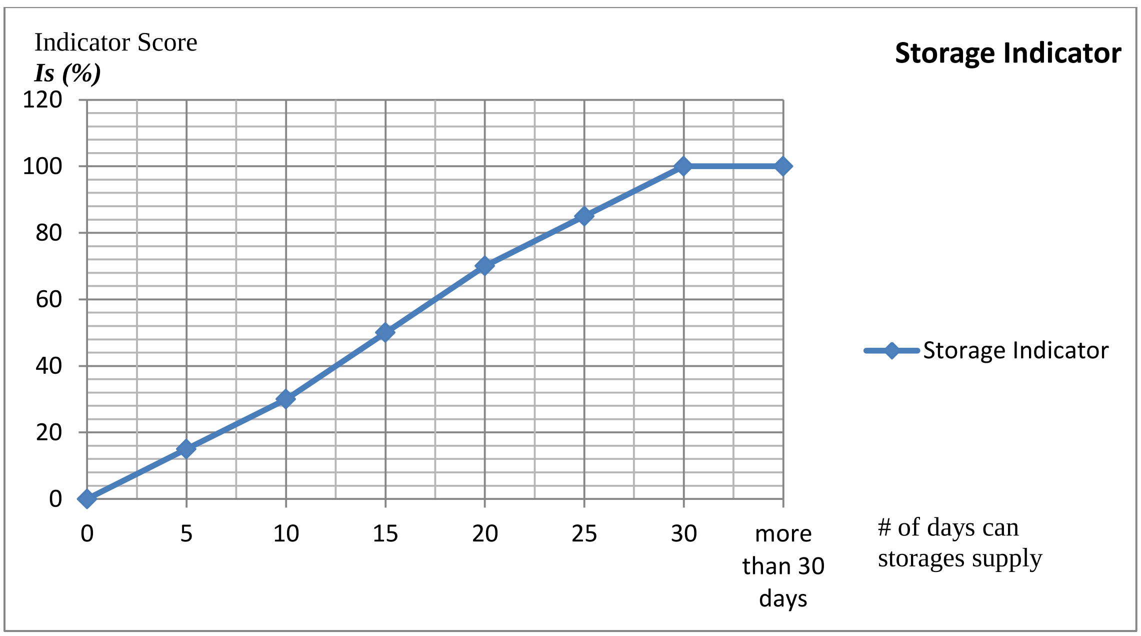


Figure 15 Storage Indicators

(2) Demand (I_D)

This indicator (I_D) looks at the capacity to supply water demand by considering population growth and future demand. It measures the number of years before the capacity to supply water will be exceeded due to population growth. It has adjusted the number of years to construct new water infrastructure in case of population growth to 10 years instead of the 50 years used in the Canadian water sustainability index. If the number of years is less than 10, the demand indicator can be determined from equation (6B) (Policy Research Initiative, 2006).

$$\mathrm{FV} = (1 + \mathrm{r})^{\mathrm{t_d}} * \mathrm{PV} \tag{6A}$$

Where FV: number of consumers who can be served at 100% of production

PV: number of consumers who can be served at current % of production

r: rate of population growth

$$I_d = \begin{cases} 100 & if\ t_d > 10 \\ \frac{t_d}{10} * 100 & if\ 0 < t_d \leq 10 \\ 0 & if\ t_d = 0 \end{cases} \tag{6B}$$

(3) Access to Safe Drinking water (I_{SWS})

This indicator (I_{SWS}) measures the percentage of unsafe drinking water reported from the Environmental Protection Agency in Kuwait. EPA in Kuwait uses certain criteria to classify unsafe drinking water. These criteria include the concentration of total dissolved solid (TDS), percentage of chlorine (Cl), and pH of water. The numbers of days with unsafe water for drinking and sanitation for each area in Kuwait are used in calculating the score.

$$I_{sws} = [1- \{\# \text{ of unsafe water days/ } n\}]* 100 \tag{7}$$

Where n is the number of days in the measuring period.

(4) Network (I_N)

This indicator (I_N) characterizes how the water network is distributed. There are many types of water networks, such as series, branches, single loops, multi-loops, multi-loops with single redundant pipelines, and multi-loops with redundant pipelines. The percentage of each type of network is provided by the Kuwait Department of Network and Maintenance of the Ministry of Electricity and Water. To determine the network indicator score (I_N), we have to find how many pipelines deliver water from sources to an area and the type of distribution of the main pipelines within the area. Table 5 assigns a score for each type of water network.

Table 5 The score of network indicator (Source: MEW, 2008)

Type of water network	**Score of sustainable network (%)**
Series	8
Branches	25
Single loop	50
Multi-loops	70
Multi-loops with single redundant pipeline	90
Multi-loops with redundant pipelines	100

- **Capacity**

This subcategory measures the overall capacity of the community to access potable water, the demand over capacity, the percentage of sustainable demand per capita from the basic daily water requirement, and water services disruption. The capacity score is the average of the four indicators in the subcategory.

(1) Resilience (C_{rs})

Resilience is the probability that if a system has a failure scenario in a certain period, the next period has no failure. Resilience shows the ability of the system to recover from a failure episode. The resilience indicator assesses the drop in water pressure in a peak period as a failure scenario. In Kuwait, each area has a constant value for water pressure (P_i) in peak periods and non-peak periods. When the system has no drop in water pressure during a peak period, the resilience indicator has a score of 100%. Figure 16 illustrates water pressure (P_i) when it is below the normal condition during peak periods. The water pressure value in non-peak periods is the upper boundary of the system, while water pressure value in peak periods (normal condition) is the lower boundary of system. Any water supply with water pressure less than the upper boundary is considered a deficit in the system.

$$C_{rs} = [\frac{[\text{No of times water pressure (P}i\text{) in WDN back to normal condition in peak period}]_i}{[\text{No.of times water pressure (P}i\text{) in WDN below normal condition}]_i}] * 100 \quad (9)$$

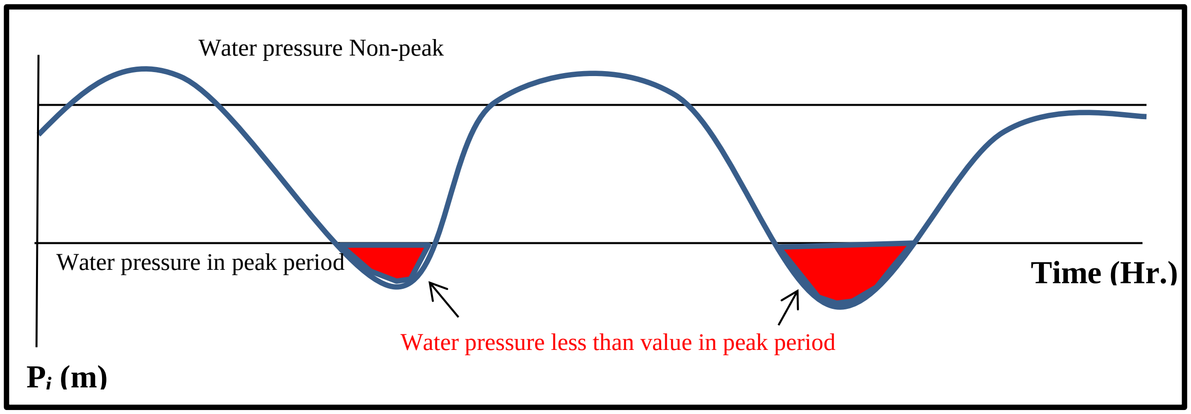


Figure 16 Water pressure in WDN in peak and non-peak periods.

(2) Access (C_a)

The access indicator (C_a) assesses the ability of the community to receive an amount of freshwater per day per capita for domestic use, based on water pressure in WDN in peak and non-peak periods. The minimum value for acceptable access per capita for domestic freshwater is 50 L/day to satisfy personal requirements, excluding water for cleaning, cooking, and bathing. If these other requirements are included, the basic personal per capita requirement is 150 L/day (Shiklomanov, 1997). The access indicator (C_a) is adopted from the Canadian water sustainability index report (Policy Research Initiative, 2005).

$$C_a = \begin{cases} 100 & if\ D_i > 150 \\ \left[1 - \frac{150 - D_i}{150 - 50}\right] * 100 & if\ 50 < D_i \leq 150 \\ 0 & if\ D_i < 50 \end{cases} \qquad (10)$$

(3) Reliability (C_r)

The reliability indicator (C_r**)** measures the fraction of time service is disrupted in a certain period. Service disruption may occur as a result of poor water quality or contamination; human error; or infrastructure issues (pipeline breakage or pump shutdown). Equation (11A) measures the number of times that service disruption occurs (D_i) within a certain period (Loucks, 1997), and the score of the reliability indicator is determined from equation (11B).

$$Risk_i = \left[\frac{\sum_t^n D_i}{n}\right] \quad \text{;(n= certain period during measuring)} \qquad (11A)$$

$$C_r = [1 - Risk_i]^3 * 100 \qquad (11B)$$

The value of reliability score has cubed to consider even small service distribution as significant concern.

(4) Consumption (C_{capita})

This indicator (C_{capita}) assesses the trend of water consumption per capita per day (D_i) for area i relative to the basic requirement for water. The goal for sustainable daily water use per capita is 150 L. To increase the accuracy of this indicator, it also considers the minimum personal requirement value of water (50 L/day). When the indicator has a high value, this means there is a reduction in water consumption to reach the desired per capita value (150 L/day) for domestic potable water.

$$C_{Capita} = \begin{cases} 100 & if\ 50 < D_i \leq 150 \\ \left(1 - \left[\frac{(D_i - 150)}{(D_i - 50)}\right]\right) * 100 & if\ D_i > 150 \\ 0 & if\ D_i < 50 \end{cases} \tag{12}$$

(b) Socio-Economic Category

This category has four indicators that demonstrate the social and economic impacts of water system demand on sustainable development. The SKI indicator scores in the socioeconomic category consider pollutant emissions from desalination plants and the percentage of government subsidy for water price. The score for the socioeconomic category is computed by the average of its indicators. Indicators in the social field usually are not directly related to the water system (Loucks et al., 2005). For example, the pollutant emissions are consequences of the lack of awareness of society of their effect on the environment. As a result of water overconsumption, desalination plants increase fuel burning in order to satisfy the water supply for entire areas in Kuwait. The most important pollutants that are emitted from desalination plants are carbon dioxide, sulfur dioxide, and nitrogen dioxide. Concentration of CO_2 in the atmosphere has to be monitored because it is one of the greenhouse gases. The reaction of NO_2 with O_3 plays a critical role in photochemical smog. It also contributes to the formation of ground-level ozone (O_3), and fine-particle pollution, and NO_2 is linked with a number of adverse effects on the respiratory system. SO_2 dissolves in rainwater to form sulphurous acid. In addition, it reflects light when released to the atmosphere and is listed by the Environmental Protection Agency (EPA) as a critical pollutant. So the SKI indicators provide the percentage of consequences of water overconsumption by measuring pollutant emissions. The applicable pollutant emissions standards based on measurements of the EPA in Kuwait are as follows:

CO_2 (million M.Tons)	SO_2 (thousand M.Tons)	NO_2 (thousand M.Tons)
91.75	778.41	458.75

Pollutant emissions should not exceed the standard mass of the environment to absorb or reduce their harm.

(1) Emission CO_2 (S_{CO2})

This indicator (Sco_2) serves as a proxy for community water consumption by looking at the CO_2 emissions per capita from burning fossil fuels to produce water. Carbon dioxide (CO_2) is the primary greenhouse gas emitted from the combustion of fossil fuels. This indicator shows the responsibility of consumers in society for releasing CO_2 emission from desalination plants due to water consumption.

$$S_{co_2} = \left[1 - \frac{(\frac{CO_2\ Emission}{Population})_i}{\left(\frac{CO_2\ Emission}{Population}\right)_{STD}}\right] * 100 \tag{13}$$

(2) Emission SO_2 (S_{SO2})

Determining SO_2 emissions as a consequence of water production is a step toward a higher sustainability level. By identifying the SO_2 emission per capita, society may take action to decrease the emissions that result from water overconsumption. The value of this indicator is calculated as:

$$S_{SO_2} = \left[1 - \frac{(\frac{SO_2\ Emission}{Population})_i}{\left(\frac{SO_2\ Emission}{Population}\right)_{STD}}\right] * 100 \tag{14}$$

(3) Emission NO_2 (S_{NO2})

The third emission indicator that reflects the role of society in increasing the quantity of pollutants released to the atmosphere is the NO_2 emission indicator, which is the amount of pollutants emitted per capita due to water production from desalination plants and reflects the consumption behavior of the community. A low score for this indicator indicates less sustainable water consumption. The indicator is calculated as:

$$S_{NO_2} = \left[1 - \frac{(\frac{NO_2\ Emission}{Population})_i}{\left(\frac{NO_2\ Emission}{Population}\right)_{STD}}\right] * 100 \tag{15}$$

(4) Subsidy (S_S)

This indicator addresses subsidies received from the government. When the government increases support with water prices, it decreases the sustainability of the water system. The role of water price is important in reducing water overconsumption. When the water price is relatively small in terms of water production cost, then the consumption will be increased.

$$S_S = \left[\frac{Water\ price}{water\ production\ price}\right] * 100 \tag{16}$$

Table 6 List of SKI indicators equations

Category	Indicators	Indicator equation
Resources	Availability	R_{av} =[1 – (Total Supply per day/ total installed capacity per day)]*100
	Renewability	$R_r = \begin{cases} 100 & if\ T > 1700 \\ \frac{T-500}{1700-500} * 100 & if\ 500 \leq T \leq 1700 \\ 0 & if\ T < 500 \end{cases}$
	Recharge	$R_{ASR} = [\frac{(\text{volume of water recovered with TDS less than 1500 mg/L})_{Cycle}}{(\text{volume of water injected})_{\text{Cycle}}}] * 100$
	Demand	$R_D = [\ (D_{STD.}/D_i)\ ] *100$
Infrastructure	Storage	$I_s = \left[\frac{\left[\frac{(\text{Reservoir volume for area})_i + (\text{Tank volume for area})_i}{(\text{water per capita for area} * \text{population})_i}\right]}{30}\right] * 100$
	Demand	$\text{FV} = (1 + \text{r})^{t_d} * PV$; $\text{I}_\text{d} = \begin{cases} 100 & if\ t_d > 10 \\ \frac{t_d}{10} * 100 & if\ 0 < t_d \leq 10 \\ 0 & if\ t_d = 0 \end{cases}$
	Safe Water	I_{sws} = [1- {# of unsafe water (days) / n}] * 100 ; n= month or year
	Network	To determine network indicator score (I_N) from table (2) it has to find: 1- How many pipelines that delivers the water from source to area 2- The type of distribution of main pipelines within area.
Capacity	Resilience	$C_{rs} = [\frac{[\text{No of times water pressure (P}i\text{) in WDN back to normal condition in peak period}]_i}{[\text{No. of times water pressure (P}i\text{) in WDN below normal condition}]_i}] * 100$
	Access	$C_a = \begin{cases} 100 & if\ D_i > 150 \\ \left[1 - \frac{150 - D_i}{150 - 50}\right] * 100 & if\ 50 < D_i \leq 150 \\ 0 & if\ D_i < 50 \end{cases}$
	Reliability	$Risk_i = \left[\frac{\sum_t^n D_i}{n}\right]$; $C_r = [1 - Risk_i]^3 * 100$
	Consumption	$C_{Capita} = \begin{cases} 100 & if\ 50 < D_i \leq 150 \\ (1 - \left[\frac{(D_i - 150)}{(D_i - 50)}\right]) * 100 & if\ D_i > 150 \\ 0 & if\ D_i < 50 \end{cases}$
Socio-economic	EmissionCO_2	$S_{co_2} = \left[1 - \frac{(\frac{CO_2\ Emission}{Population})_i}{(\frac{CO_2\ Emission}{Population})_{STD.}}\right] * 100$
	Emission SO_2	To find the indicator score S_{SO2} :Same the equation above with SO_2 Emission
	EmissionNO_2	To find the indicator score S_{NO2} : Same the equation above with NO_2 Emission.
	Subsidy	$S_S = \left[\frac{Water\ price}{water\ production\ price}\right] * 100$

4.3.2. Sustainability of Water System and Infrastructure of Kuwait (SWSIK)

The Sustainability of Water System and Infrastructure of Kuwait (SWSIK) tool is a comprehensive analytical tool to integrate environmental, economic, social, and infrastructural variables for a water system. The SWSIK tool provides an opportunity to control, describe, and predict the effect of these variables on the water system. The SWSIK tool evaluates the sustainability performance of a water system in a two-dimensional approach, and then it indicates the effective benefits for each approach.

First, the effects of water price scenarios on the triple bottom line of sustainability (environment, economic, social) are evaluated from both economic and environment perspectives. Water price policies are evaluated by SWSIK to compare the benefits of the environmental, economic, and social dimensions of the water system. Water price is the critical variable that can change social behavior related to water, thus reducing water overconsumption. A previous study was conducted in MIT-Kuwait center to tests alternative proposal of water demand models (Milutinovic, 2006). These models were developed in this research by using real data of Kuwait and test coefficients correlated to simulate the model in correct track. Water demand model can be used to compute the growth or reduction of water consumption based on the water price variable

The second task of SWSIK is to analyze and evaluate water infrastructure, looking intensely at weakness in the operation of water distribution networks (WDNs) and the damage that could happen to the network. By incorporating the three performance criteria of reliability, resiliency, and vulnerability of WDNs (Bentes et al., 2011; Pinto et al., 2010a; Pinto et al., 2010b), the SWSIK tool can identify the most vulnerable part of

WDNs from the Theory of Vulnerability Water Pipe Networks (TVWPN). TVWPN was derived from structural vulnerability theory (SVT) applied to water infrastructure (Agarwal et al., 2001a, 2001b; Pinto et al., 2002; Lu et al., 1999; Wu et al., 1993; Yu, 1997).

4.3.2.1 Evaluating the Effect of Water Price on Sustainability Using SWSIK

The SWSIK tool can be used to evaluate the current water price in Kuwait \$0.624/m^3 and the proposal water price to show the economic and environmental aspects of water consumption for each zone in Kuwait. First, SWSIK determines the energy needed from fossil fuels of desalination plants (crude oil, high-fuel oil, gas oil, and natural gas) to produce a specified volume of water. Second, emissions from burning fossil fuels to produce freshwater are computed by the fuel-analysis approach (EPA, 2008). This depends on mass balance equation to determine the molecular weight of the pollutants and fuels. The properties for each fuel are listed in Appendix 1. Percentages of fossil fuel volumes used in desalination plants in Kuwait are assumed based on the average for the fuels (MEW, 2011). When fuel is burned, most of the pollutants emitted are CO_2, NO_2, and SO_2.

The economic approach of SWSIK determines the cost of fossil fuels and the total cost of water consumption for each zone. The cost of fossil fuels is 45% of the total cost. The government subsidy can be found based on the water price variable and total cost to produce freshwater, i.e., the difference between the total water productions cost from desalination plants and the water-selling price. SWSIK measured the awareness and interaction in Kuwaiti society with water over-consumption by survey that was published in social networks (Twitter and Facebook) and the Alwatan online newspaper. Overall, this approach reflects the benefits of using water price policy to reduce water over-consumption. Figure 17 shows the processes through which SWSIK obtains the economic and environmental results of the current water price scenario.

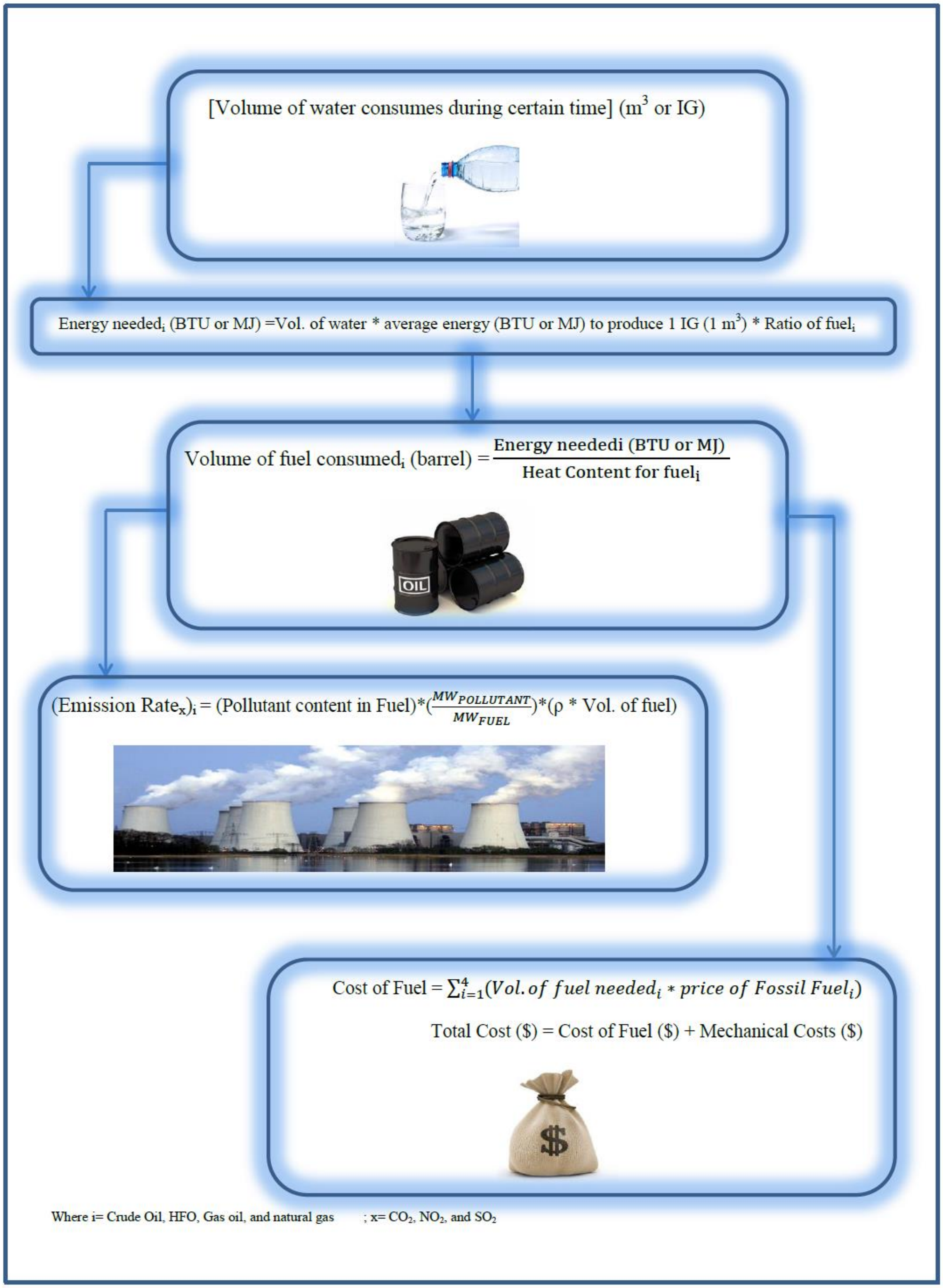


Figure 17 The process of SWSIK to defines Economic and Environment aspects

4.3.2.2 Theory of vulnerability of Water pipe network (TVWPN)

The most vulnerable parts of WDNs and other factors that may lead to damage to the water system in some situations can be identified through the use of the Theory of Vulnerability of Water Pipe Network (TVWPN) (Pinto et al., 2010). WDNs are structural forms containing joints (vales, tanks, and reservoirs) and pipelines arranged and connected together, and they are represented by a *graph model* (Pinto et al., 2010). *Clusters* are defined as sets of nodes and links of a network with similar specifications. TVWPN focuses on pipelines as critical parts of WDNs, also called water pipe networks (WPNs). A *WPN cluster* is a subset of a WPN in which pipelines with similar characteristics are grouped. A *WPN ring* is represented by two WPN clusters connected so that water can flow between different junctions. There are two types of WPN rings: (1) closed rings, or loops, have pipelines arranged in parallel; and (2) open rings are arrangements of pipelines in series. WPN *branch clusters* are clusters that have more than one *leaf cluster,* that is, a single pipeline and contiguous joints. A tank or reservoir is a *WPN reference cluster* that causes damage to the WPN system to occur immediately if it is separated from the system. The *WPN root cluster* contains WPN systems and WPN reference clusters. A *WPN deteriorating event* is the damage that leads to loss of supply due to broken pipes or water storage. A *WPN vulnerable failure scenario* is a series of WPN-deteriorating events that decrease the performance of supply (Pinto et al., 2010).

4.3.2.3 Work Procedure of the TVWPN

The application of TVWPN is conducted through three processes: (1) clustering; (2) hierarchical model formation; and (3) unzipping. The application of TVWPN is a series of processes in which each technique relies on the preceding step.

4.3.2.4 Processes of TVWPN

TVWPN depends on many factors to find the most vulnerable part of a WDN in clustering and unzipping. Well-formedness (ΔH_L) is the total head loss in the pipes. The head loss is influenced by the properties of pipes, types of joints, configuration of the WDN, and connectivity. Nodal connectivity (η) is the number of pipes that come together at WPN branch cluster joints. Damage demand (E) is the design pressure of the pipe. Relative damage demand (E_r) is the ratio of damage demand to the maximum damage demand (E_{max}) in the WPN. The distance between the cluster and a storage tank is represented by D_{SI}. Separateness (γ_r) measures the ratio of loss in the WPN after deterioration events. It is the total head of deteriorated parts to the total head of the whole WPN. For a given failure situation, the vulnerability index (φ) is the ratio of relative damage demand (E_r) to separateness (γ_r). The value of vulnerability index gives an indication of the degree of vulnerability of the WPN.

(a) Clustering process

The clustering process is the basic technique for identifying and evaluating the vulnerability and connectivity of a WPN. It is a selective process that depends on the clustering criteria to choose candidate WPN branch clusters (WPN rings) at each step.

The selective process is repeated to form higher levels of hierarchy until it reaches the last level, which contains the whole WPN (WPN root cluster). The following clustering criteria, in order, are used to select WPN branch clusters from WPN leaf clusters:

- minimum total head loss (ΔH_{min})
- maximum damage demand (E_{max})
- maximum nodal connectivity (η_{max})
- maximum distance from a storage tank (D_{ISmax})
- free choice (F_C); the decision belongs to policymakers

In order to demonstrate the application of TVWPN, the WPN shown in Figure 9a is used to explain clustering, hierarchical model, and unzipping processes. Four pipes, four joints, and single storage characterize the WPN example. The hydraulic properties for WPN design are 0.01 mm roughness and 0.6 MPa service pressure (damage demand). The head loss value results for WPN design are given in Figure 9a. The clustering process is shown step by step in Figure 9. Since clustering is progressive, the following points are used to analyze and illustrate the clustering process:

❖ The first step is identifying the candidate WPN branch cluster (made up of joints and pipelines)

   ➢ Candidate 1 (Pipes 1 and 2): Head loss is 2.049 m, E=1.2 MPa, η=2, D_{IS}=0
   ➢ Candidate 2 (Pipes 1 and 4): Head loss is 1.967 m, E=1.2 MPa, η=2, D_{IS}=0
   ➢ Candidate 3 (Pipes 3 and 2): Head loss is 2.108 m, E=1.2 MPa, η=3, D_{IS}=500 m
   ➢ Candidate 4 (Pipes 4 and 2): Head loss is 2.026 m, E=1.2 MPa, η=3, D_{IS}=500 m
   ➢ Candidate 5 (Pipes 3 and 4): Head loss is 2.026 m, E=1.2 MPa, η=3, D_{IS}=500 m

- According to vulnerability criteria for clustering, candidate 2 (Pipes 1 and 4) makes the new branch cluster 6. Figure 9b shows the first step of the clustering process.
- Again, identifying the candidates WPN branch cluster
  - Candidate 1 (Pipes 3 and 2): Head loss is 2.108 m, E=1.2 MPa, η=2, D_{IS}=500
  - Candidate 2 (Pipes 2 and 6): Head loss is 3.021 m, E=1.8 MPa, η=0, D_{IS}=0
  - Candidate 3 (Pipes 1 and 2): Head loss is 2.021 m, E=1.8 MPa, η=0, D_{IS}=0
- The second step in the clustering process is selecting candidate 1 to be the WPN branch cluster 7
- Branch clusters 6 and 7 are the only candidates, so they form branch cluster 8
- At this stage of analysis, the last WPN branch cluster is formed from the reference cluster (water storage) and branch cluster 8. Figure 9e shows the last WPN branch cluster, which is the root cluster.

(b) Hierarchical model formation

The hierarchical model formation is created by the clustering process. It is an alternative graphical way to represent the whole WPN and the WPN rings. The starting point to understanding the hierarchical model is from bottom to top. WPN rings represent new branch clusters, and the criteria are used to select candidate leaf clusters. In general, hierarchical models are used in many fields, such as medical cell division, animal breeding, and genealogy (Pinto et al., 2010).

Figure 10 shows the clustering process in a graphic. The hierarchical model for the WPN example is drawn based on the information obtained during the clustering process. Understanding the hierarchical model in Figure 10 requires beginning from the bottom of the model, which represents all leaf clusters. The top of the hierarchical model is the root cluster.

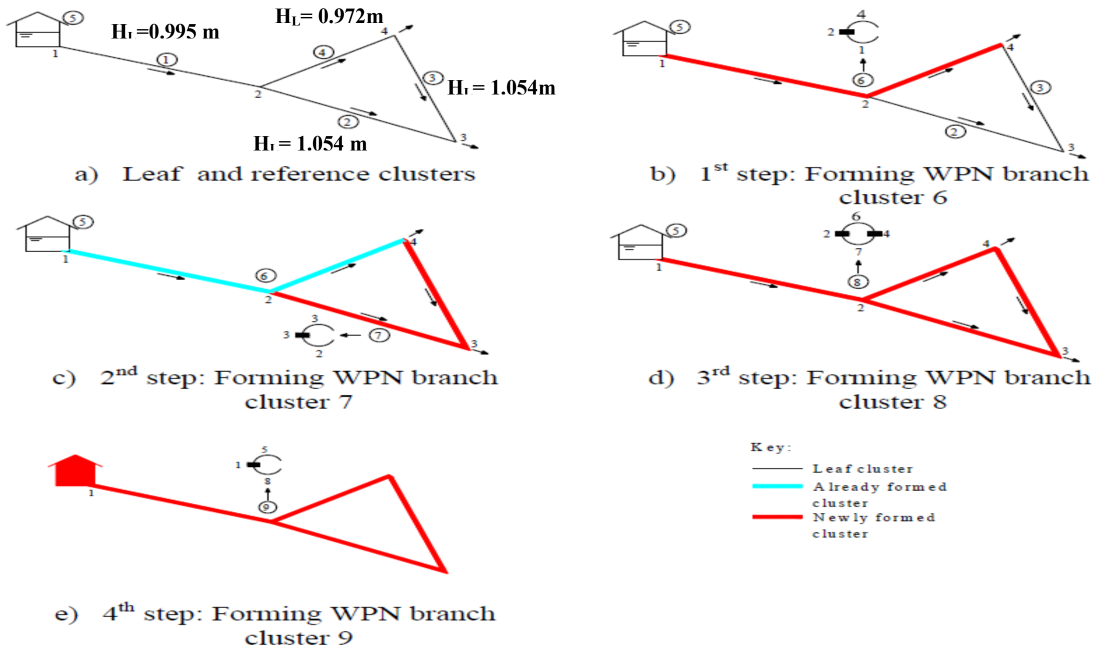


Figure 18 Example of clustering process of a WPN (Citation: Pinto et al., 2010)

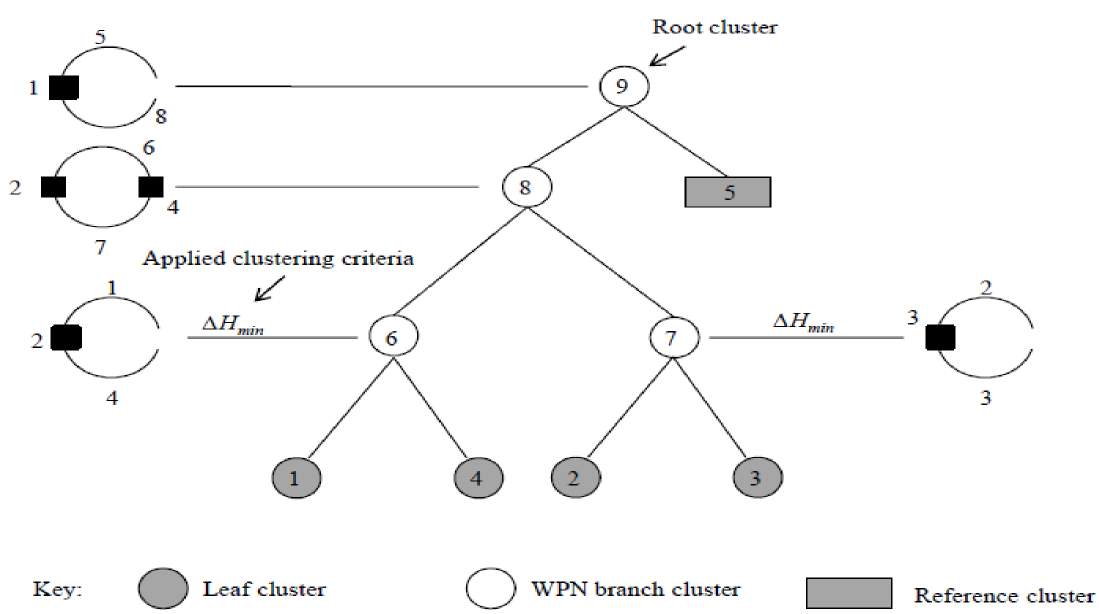


Figure 19 Example of Hierarchical model of the WPN (Citation: after Pinto et al., 2010)

(c) Unzipping process

Unzipping identifies the vulnerable WPN failure scenario by unzipping the hierarchical model from the top down. The following unzipping criteria are used to identify the WPN vulnerable failure scenario among all the WPN branch clusters:

- A cluster is not a reference cluster (N_R)
- It connects directly to the reference cluster (C_D)
- It is a leaf cluster rather than a WPN branch cluster (L_C)
- It has a higher value of head loss ($S_{\Delta H}$)
- It has the smallest value of damage demand (S_E)
- It was clustered the latest (C_L)
- Free choice (F_C); the decision belongs to policymakers to determine the failure part in WPN

Based on the hierarchical model in Figure 10, the search for a vulnerable failure scenario is achieved by applying unzipping criteria. The following procedure illustrates the unzipping process (figure 11):

- ❖ Branch cluster 9 has two paths, and the path to branch cluster 8 is selected according to the first unzipping criteria (N_R)
- ❖ Moving down the hierarchical model, branch cluster 8 was formed from branch clusters 6 and 7. Based on the second criteria of the unzipping process, branch cluster 6 was formed from leaf cluster that connect to the reference cluster (C_D)

The candidates to be properly damaged are leaf clusters 1 and 4. By applying the unzipping criteria, leaf cluster 1 is the vulnerable part of the WPN example. So if leaf cluster 1 (pipe 1) is damaged, then total failure will occur and the whole WPN will not receive water.

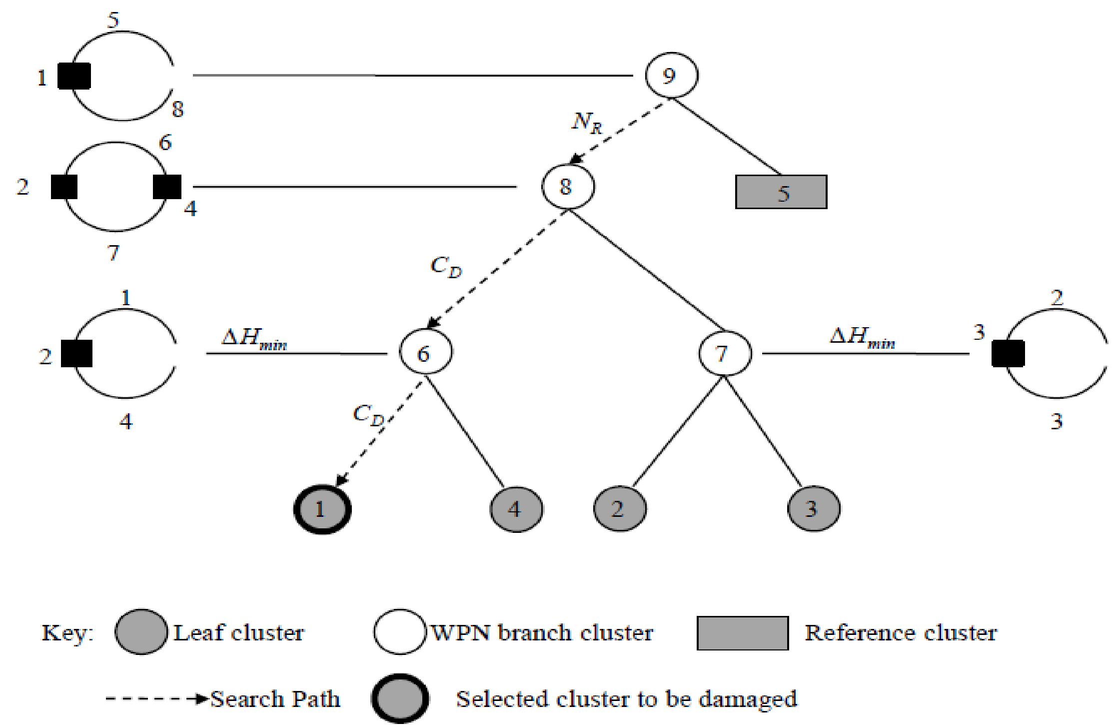


Figure 20 Example of unzipping process of the WPN (Citation: after Pinto et al., 2010)

4.4. Activity 3: Water Demand Model in Kuwait

The main objective of this section is to illustrate the benefits of water price structure scenarios to reduce water consumption by using the water demand models that were developed at MIT- Kuwait center, and then adapt the optimum approach for the Kuwait water system. The design of a water price structure is a crucial issue for integrated water management and is necessary for achieving sustainable consumption that can save natural resources in Kuwait. The SWSIK tool is used to show the benefits of the proposed water price structure and the impact of the water price scenarios on the sustainability of water system developments. Also, it will reflect the effect of government subsidies for water. Moreover, price elasticities of water demand can be determined from water demand model. Two previous models (Abu-Rizaiza, 1991, Ayadi et al., 2002) were used to test the impact of water price structure on residential water usage and to develop water demand model for Kuwait based on specific speciation . This approach can provide decision makers with the ability to select the optimum water price structure that can reduce the demand for both water and energy in terms of population growths for the coming years. SWSIK will be applied to describe, predict, and control the pattern of water demand and consumption and the analysis of a critical infrastructure system.

4.4.1. Water Price Structure

Water price structure can play a crucial role in water demand management. Most of the previous studies have confirmed that water price policy has a significant impact on controlling and maintaining water consumption. Future increases in water demand in Kuwait will continue to put pressure on the limited water resources, increasing government subsidies, and exacerbating environmental issues due to increased production from desalination plants. Water demand in Kuwait was around 464 L/Capita/day in 2011.

A sustainable water pricing structure can lead to reduced pressure on water resources, reform the water consumption behaviors of consumers, ensure that water infrastructure is adequately designed, and postpone and downsize water infrastructure projects. There is a proven elasticity between increased water prices and water consumption (Dalhuisen et al., 2003). Water demand models provide an option for policymakers to decide (1) what type of price structure to use and, (2) the most sustainable price to charge consumers. There are many types of water price structures that have been used to charge consumers, such as:

- Monthly flat rate
- Constant prices
- Block pricing
- Free allowance followed by various pricing schemes

The necessity and ability to have a new water price policy in Kuwait was considered a central question in this research. One of the objectives of this research is to propose a new water price policy in Kuwait to reduce wasteful water consumption and develop a water demand model that can determine water usage at alternative water price scenarios. Previous water demand models from the Kingdom of Saudi Arabia (KSA) and Tunisia were adapted to develop a water demand model in Kuwait. Water demand models simulated the two proposal scenarios of water price structure. The first scenario involved computing monthly water usage per household based on a constant water price, and the second scenario involved charging for water use that is in excess of free allowance.

4.4.2. Water demand models

A number of simulations analyzing the two water pricing scenarios were conducted for propose a new water price policy in Kuwait. The first scenario involves a constant price in the range of \$0.6-2.6 per m^3. The range of water prices was selected based on the following; the current water price is \$0.624 then the minimum value was selected \$0.6 and water price at \$2.6 gives water usage equals to 150 L/c/d. The second scenario involves providing a quantity of freshwater to consumers free of charge, and any water consumption over the free allowance is charged at constant price. Two previous water demand models were adapted to this research to determine the domestic water usage per household in Kuwait. The models of Tunisia and Saudi Arabia were selected, due to their common traditions and cultures with Kuwait. The Saudi Arabia model (SA) provides two approaches. The first approach is used when applying a new water price policy for the first time without a non-water price policy. The second approach is used after the consumption behavior has changed and with a well established non-water price policy. Using efficient devices to reduce water flow and advertisements in public places to conserve water are some of types of non-water price policy. The two water demand models were used to simulate the effect of water price on water demand dependent on the following variables:

- Water price
- Household income
- Household size
- Average temperature

The following equations were used to determine water consumption per household:

<u>Saudi Arabia Model (SA) (Abu-Rizaiza, 1991)</u>

$$\text{Log}(Q)=\alpha_0+\alpha_1.\ \text{Log}(INC)+\alpha_2.\ \text{Log}(P)+\alpha_3.\ \text{Log}(FSIZ)+\alpha_4.\text{Log}(TEMP) \qquad (17)$$

Q: annual water usage per household

INC: annual Household Income

P: Water Price

FSIZE: number of family member per households

TEMP: annual average temperature

Since the only point that was known between the demand and water price relationship was 464 L/Capita/Day for \$ 0.624 per m^3, the interception (α_0) was the only coefficients different from the SA model coefficients. Coefficients were tested by statistical package analysis to reach the required correlation. SA model is logarithmic and was applied on an annual scale.

<u>Tunisia Model (TU) (Ayadi et al., 2002)</u>

$$\text{Log}(C)=\alpha_0+\alpha_1.\ \text{Log}(R)+\alpha_2.\ \text{Log}(P)+\alpha_3.\ *\ \text{Log}(FSIZ) \qquad (18)$$

C: monthly water usage per household

R: monthly Household Income

P: water Price

In the Tunisia Model (TU), a family size per house variable (FSIZ) was added to the equation to be more realistic and to determine water consumption based on a household. The TU model divided the consumers into two groups and each group has specific coefficients.

4.4.3. Assumption and input for water demand models

Both models mainly depended on household (HH) size and income variables as input to develop a water demand model for Kuwait. Milutinovic (2006) tried to make certain assumptions by using U.S. data and then using the ratio of GDP for both countries to convert them to Kuwait data. In this research, the actual data regarding the distribution of household (HH) size and income were provided by Kuwait government (Public Authority For Civil Information, 2013). Kuwait provides many opportunities to find jobs with good pay and excellent life standard, so the percentage of non-Kuwait workers was around 52.5 % in 2011. There are three types of foreigners working in Kuwait: 1) home laborers who are working as maids and drivers in Kuwaiti and non-Kuwaiti homes (this group of people does not need to pay electricity and water bills; the household owner pays instead); 2) people who have homes in Kuwait and work as well 383,946 families (these non-Kuwaiti pay utility bills since there are residents in Kuwait; 3) laborers (foreign) brought in by private companies to work completing simple tasks in fields (these laborers stay on company properties, and companies deduct water bills from their salaries). The total number of Kuwaiti households was 240,087 in 2011. Due to the diversity of the types of home laborers in Kuwaiti homes, the assumption was made and assigned based on the following:

- Each HH size of 3 persons has 1 home laborer.
- HH size of 4 and 5 members has 2 home laborers.
- HH size of 6, 7, and 8 members has a minimum of 3 home laborers.
- HH size of more than 9 residents has 4 home laborers.

On other hand, the assumption for non-Kuwaiti families who work in Kuwait was 1 home laborer for HH of more than 2 persons. Table (7) shows the distribution of Household (HH) size in Kuwait with and without home labors (HL).

Table 7 The Distribution of Households (HH) size in Kuwait in 2011 (Source: PACI, 2013)

HH SIZE	HH Kuwaiti %	HH Non-Kuwaiti %	HH size w/HL for Kuwaiti	HH size w/HL for non-Kuwaiti
1 member	9.5	45.8	1 member	1 member
2-3 members	14.1	24.0	2- 4 members	2-4 members
4-5 members	15.6	17.9	5-7 members	5-6 members
6-7 members	17.7	6.6	8-10 members	7-8 members
8-9 members	16.1	2.5	11-13 members	9-10 members
10-11 members	11.6	1.4	14-15 members	11-12 members
12-13 members	6.7	0.8	16-17 members	13-14 members
14+ Members	8.7	1.2	18+ Members	15+ Members

Household income for Kuwaiti and non-Kuwaiti were divided into five classes. Tables 8 and 9 show the number of households in each income class for Kuwaitis and non-Kuwaitis. Both tables appear to show that Kuwaiti households earn slightly more than non-Kuwaiti households due to certain privileges granted to citizens by the Kuwaiti government. Household income figures for Kuwaiti families were obtained from the statistics office in The Public Authority For Civil Information. For each income class the average value of income was taken and used as input for the income variable in water demand models.

Table 8 The distribution of Household size along income ($/month per household) classes for Kuwaiti (Source: PACI, 2013)

HH size (2011)	HH Kuwaiti	Less than $ 2827	$ 2827 - $ 5300	$5300 - $ 8834	$8834 - $12367	More than $ 12367
1 member	22813	5125	7563	8563	1000	562
2-3 members	33810	4762	10464	10762	5060	2762
4-5 members	37404	3481	4001	10481	12481	6960
6-7 members	42450	4490	10490	12490	8490	6490
8-9 members	38767	3754	3754	8753	12753	9753
10-11 members	27825	1565	1065	2565	12065	10565
12-13 members	16131	227	200	500	8752	6452
14+ members	20887	78	178	177	10177	10277

Table 9 The distribution of Household size along income ($/month per household) classes for non-Kuwaiti (Source: PACI, 2013)

HH size (2011)	HH Non-Kuwaiti	Less than $1060	$1060 - $ 3180	$3180 - $ 4240	$4240 - $ 7067	More than $ 7067
1 member	175705	92490	58560	20500	3155	1000
2-3 members	92005	10000	30000	21500	28400	2105
4-5 members	68668	684	46876	15488	4020	1600
6-7 members	25181	50	14200	8450	1181	1300
8-9 members	9574	50	5100	3500	524	400
10-11 members	5384	20	2190	2100	860	214
12-13 members	2955	54	451	450	1000	1000
14+ members	4474	32	650	1200	2400	192

To develop a water demand model based on more accurate and real data, the total groups were inserted in the model as follows: 16 groups of HH size for both Kuwaitis and non-Kuwaitis, with each group divided into 5 income classes; there is one group (49170) of people who are working for private companies and paying their water bills—their assumed income was $175 per person per month. Every income class was divided according to household size into eight groups for Kuwaitis and non-Kuwaitis. So, the total input in the water demand model contained 81 variables that represent the total population of Kuwait.

Table 10 Total distribution of population in Kuwait (Source: PACI, 2013)

#	Variable	# Of people

1	Kuwaiti	1,755,441
2	Non-Kuwaiti	1,120,291
3	Home Labors in Kuwaiti Homes	613,904
4	Home Labors in Non-Kuwaiti Homes	158,486
5	Non-Kuwaiti in Private companies	49,170
Total	**Population**	3,697,292

Saudi Arabia Model (SA)

Two approaches were used to simulate the effects of water price on water consumption using the Saudi Arabia Water demand model. The first approach applies if it is the first time there is a change in the water price and there are no conservation plans distributed by different media outlets, such as T.V., Radio, brochures, advertisement in streets, etc. The second approach, however, is implemented if there are conservation plans. All the coefficients in the first approach (SA 1) were the same values used in the original study (Rizaiza, 1991) except interception, which was modified to obtain the only value known, 464 L/Capita/Day at \$ 0.624 per m^3. In the second approach (SA 2), interception and the price coefficient have been changed to 0.213 and -0.88, respectively.

Tunisia Model (TU)

The authors of the Tunisia water demand model divided the consumers into two blocks (Ayadi et al., 2003). As mentioned before, there are 5 income classes containing the distribution of household size. The low block represents the lower three income classes and the highest income classes are combined in the upper block. All coefficients were modified to be equal or close to the coefficients used in the Saudi Arabia Water demand model. The household size (family size) variable was added to the equation but used without the logarithm term.

Table 11 The coefficients of water demand models for the original model and Kuwait Model

Model	Interception		C (Income)		C (Price)		Family size		Temperature	
	Original Model	Kuwait	Original Model	Kuwait	Original Model	Kuwait	Original Model	Kuwait	Original Model	Kuwait
SA 1 Model	0.847- (-0.16)	0.234	0.09	0.09	-0.78	-0.78	0.44	0.44	1.26	1.26
TU Model (Lower Block)	3.1	0.5	0.06	0.09	-0.08	-0.60	-	1.1-1.4	-	-
TU Model (Higher Block)	8.65	0.51	0.05	0.08	-0.34	-0.88	-	1.1-1.4	-	-
SA 2 Model	-	0.213	-	0.09	-	-0.88	-	0.44	-	1.26

Statistical package analysis was used to test the coefficients correlation between observed data and predicated data. This analysis to proves and validates that the coefficients were used in both models is applicable for water demand model of Kuwait. First, r-square (r^2) was 0.9105 for SA water demand model based on Kuwait data set. Second, the coefficients correlation for Tunisia water demand model were tested by r-square (r^2) and it was 0.8538. The mean squared error (MSE) is definitely the most important benchmark that used to evaluate the performance of predictors or independent variables. MSE is the sum of squared errors divided by the degreed of freedom. Number of observations and (n) and number of independent variables (p) are used to find the error degrees of freedom (n-p-1). The following equation was used to determines for SA and TU models:

$$\text{MSE} = \frac{\sum_{i=1}^{n}(observed\ data - predicated\ data)^2}{n-p-1}$$

MSE values for both SA and TU models were 4.3 and 0.445, respectively. The low values for MSE indicate the coefficients are highly correlated to water demand models of Kuwait.

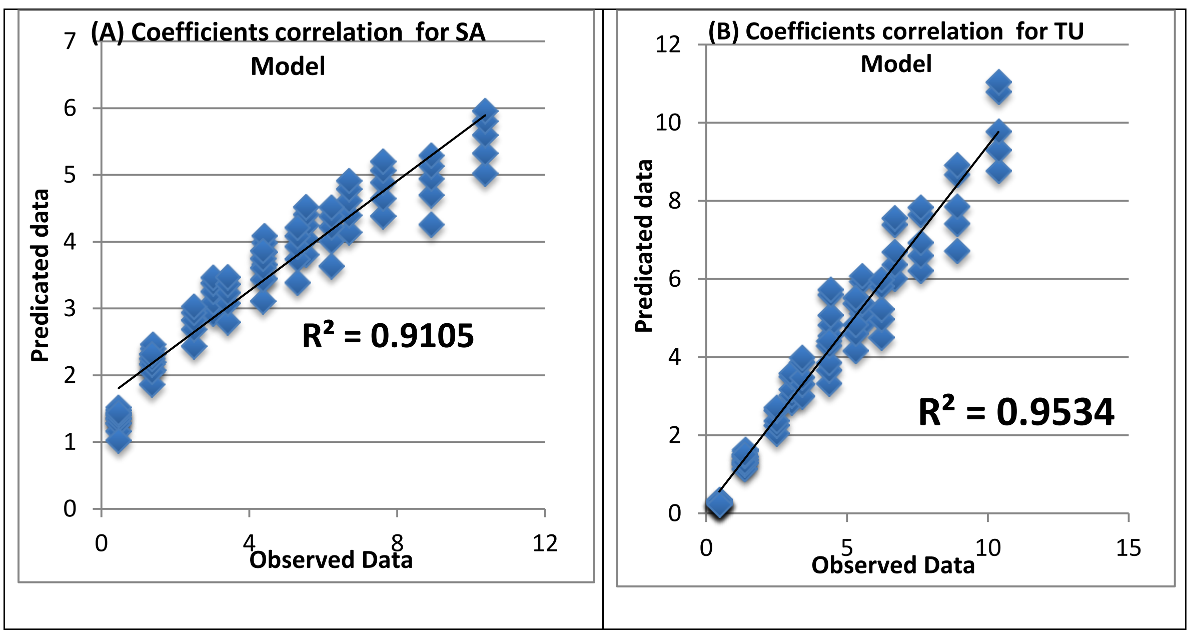


Figure 21 Observed and predicated values for (a) SA model (b) TU model

4.4.4. Water price schedule Scenarios

The main purpose of reforming the water price schedule is to evaluate the role of water price in reducing water consumption, decreasing the environmental impact, postponing water projects, and reducing government subsidies for water. Also, it will help change the consumption behavior of customers by giving them an acceptable economic value for each water unit. This research provides solutions to collecting revenues from selling water with a sustainable water price, and reducing water consumption. The following actions should implemented to achieve these results:

- Install prepaid smart water meters in homes.
- Connect water networks to GIS systems to monitor water consumption.
- Implement a new water price schedule.

Next, the SWSIK tool was used to analyze the effect of the new water price schedule on water consumption to show the economic and environmental perspectives. The proposal of new water price schedule scenarios test water consumption is based on 5 years of simulation (2013 to 2017). A comparison of the current water price based on 5 years (2013 to 2017) with a different proposal of a new water price schedule shows the progress of water consumption with the installed capacity of desalination plants. Overall, the Sustainable Kuwait Index (SKI) determines the sustainability level at a different water price schedule.

4.4.4.1 First option

The first scenario involves applying a constant price for water. The range of water price is between \$0.6 and \$2.6 per m^3. The purpose of this scenario is to compare the current price with the proposed prices in term of government subsidies, elasticity, and water consumption reduction. The SA and TU models were used to simulate the constant water price scenario.

4.4.4.2 Second option

Free allowance followed by a constant water price is the second proposed water price scenario. Two parameters (free allowance and constant price) are included in the price formula. Both water demand models used average price as the input variable. For policymakers this scenario may be acceptable, especially if it provides water free of charge and eliminates wasteful water consumption. This scenario allows the consumers to track their consumption to keep it below or close to the free allowance water limit. The Kuwait government is responsible for providing water to residents. On the other hand, the consumers have to consume less water to save natural resources and sustain future generations. With high subsidies, the current water price gives zero economic value to the consumers. So the free allowance followed by a constant price can provide a sustainable water price schedule and reform consumption behavior.

$$AP = \left[\frac{Q-APM}{Q}\right] * P \qquad (19)$$

Where Q= Water demand at Constant price + APM

APM= the allowance of water with free of Charge

P= water price between [$ 0.6- 2.6 per m^3]

CHAPTER 5: Results and Discussion

5.1. Implementing Model Urban City (MUC)

Model Urban City (MUC) is sustainable modeling solution that provides a detailed dataset that can be used to effectively evaluate water systems and their sustainability. The structure component has feature classes (pipes, pumps, tanks, reservoirs, valves, and junctions), demand tables, and raster layers that are added to the ArcGIS view to implement the scenario and system boundaries of the water system. The scenario component represents the time (past, current, or future event) in which the hydraulic data are used in the structure component and water consumption pricing policy during the same period. Influential factors shape the boundaries of the water system modeling. Table 12 characterizes the scenario and boundaries that are used to implement the MUC by the Infowater application.

Table 12 The scenario and boundaries that are used to implement the sustainable modeling solutions (MUC)

MUC component	Description
Scenario	• Time of Period: 365 days in **2011** • Water consumption Price: $ 0.624 per m^3
Boundaries	• Spatial Limitation: Urban Areas (78 areas) • Temporal Limitation: Time step is computed per Day • Water consumption pattern: assume the same during simulation (Fig.13) • Population: total population for year 2011

The InfoWater application was used to simulate the MUC scenario for 2011 data for 31 days with a water consumption pattern that represents the demand per hour. The simulation output shows the hydraulic properties and connectivity of water infrastructure. The report manager demonstrates the results by either a report or graph for junctions, tanks, or pipelines.

5.1.1. The Water Distribution Network and Zoning

Water infrastructures were classified into 10 zones by the Ministry of Energy (electricity and water) based on the elevation and type of building (towers or houses). Water infrastructures were organized into many zones to facilitate maintenance operations and find where the defects and breakdowns in the network. One of the advantages of MUC was an imported zones map in AutoCAD that was illustrated in ArcGIS. This can help determine the percentages of water consumption per zone. Also, the integration of the water distribution network zones within the Model Urban City can define reliability, resilience, and connectivity in the zone.

Table 13 The percentages of total water demand for zones

Zone	The percentage of total water demand	Water head (m)	Elevation (m)	Zone	The percentage of total water demand	Water head (m)	Elevation (m)
. Zone 1 + 4	43%	62	5 - 23	. Zone 6 A	3%	75	25 - 47
. Zone 2 + 3	30 %	85	20 - 50	. Zone 6 B	3%	75	25 - 47
. Zone 1A	16 %	65	5 - 23	. Zone 7	1%	90	40 -62
. Zone 5	1 %	125	65 - 85	. Zone Wafra*	2%	55	15 -25

*Agriculture Zone that located in south of Kuwait city

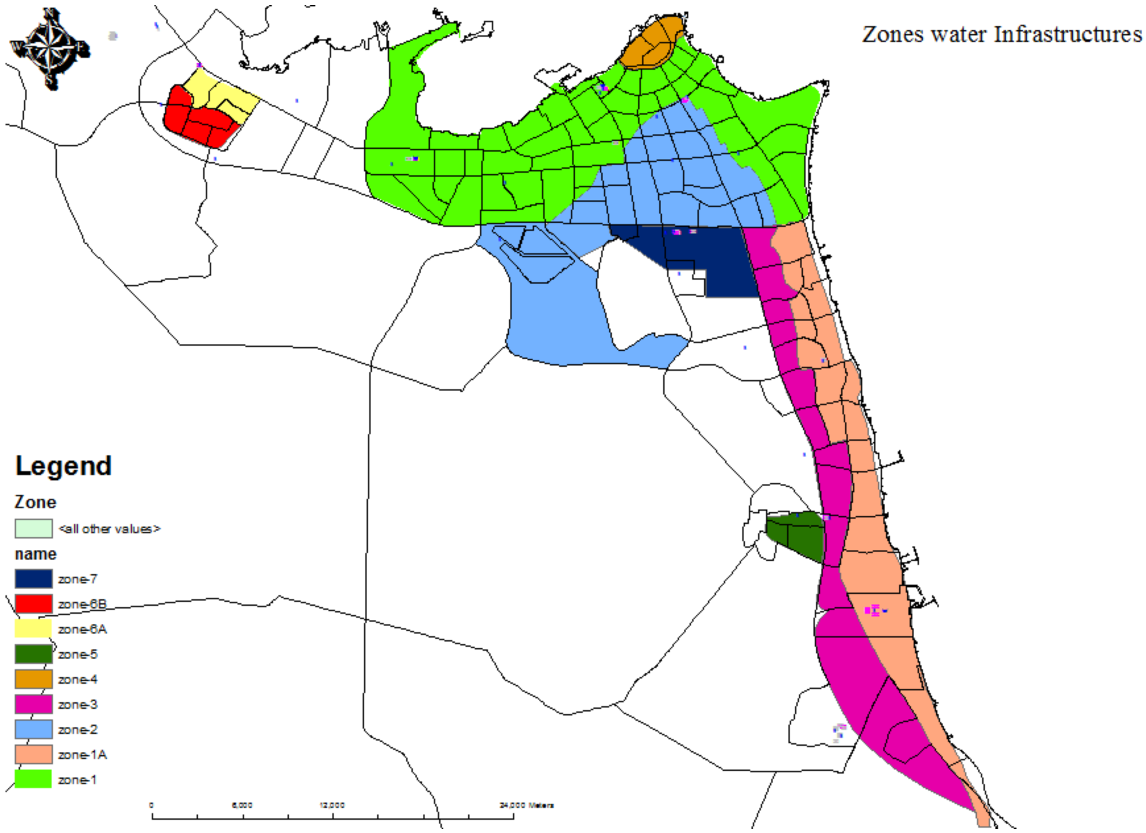


Figure 22 The distribution of Zones in Kuwait

Table 13 shows what percentage of water each zone receives from the source. The percentage of total water consumption for each zone will be considered as a constant value during future simulated scenarios.

5.1.2. Hydraulic Model Structure

The level of detail in the water distribution network is an important factor to obtain more realistic and accurate results (Edwards et al., 2009). At the stage of importing and creating a water distribution network in ArcGIS, the purpose was to provide a real network in ArcGIS based on available data provided from MEW. Two out of four types of hydraulic model structures were used to represent the Kuwait water infrastructures. The first type is called the All-Pipes Reduced Model (APRM), which has main, transmission, and smaller pipes with significant nodes along them, Fig. 24. The Skeletonized Model (SK) demonstrates that the rest of areas that have no sufficient data for smaller pipes. Typically, the skeletonized model has all the pipelines that deliver freshwater except pipes that are connected to houses.

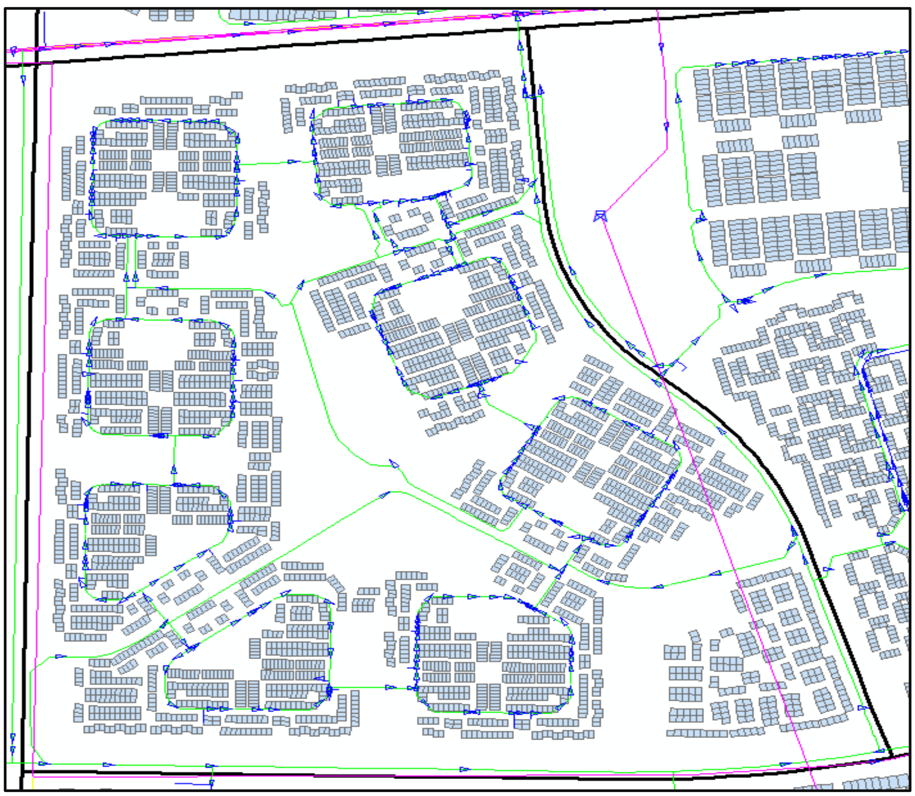


Figure 23 All-Pipes Reduced Model (APRM)

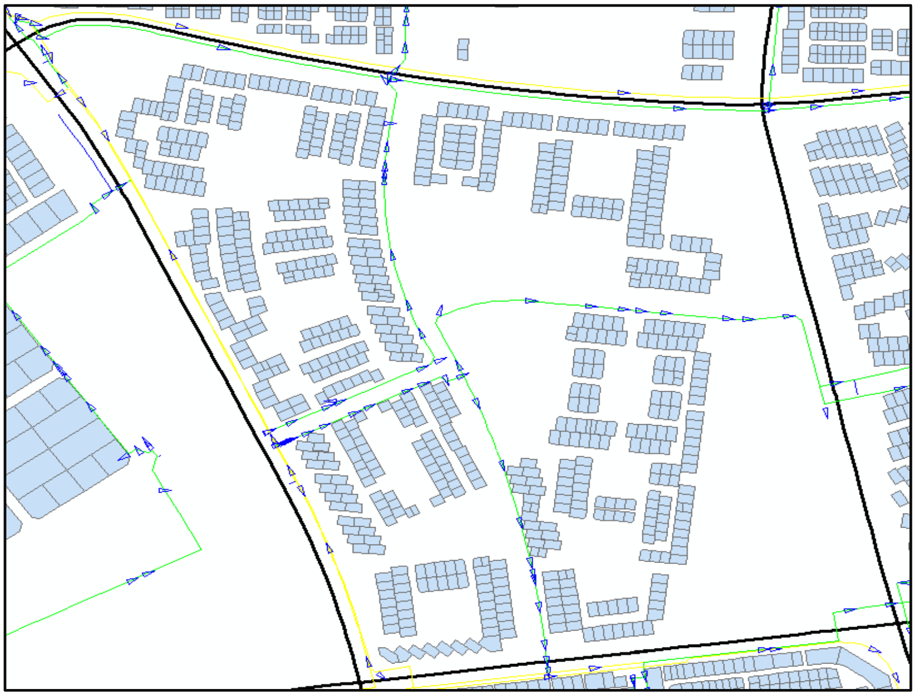


Figure 24 The Skeletonized Model (SK)

5.2. Evaluating the effect of water consumption price on sustainability by SWSIK tool

SWSIK provides two distinct approaches to evaluate improvement the sustainability of a water system. The first approach of the SWSIK tool is an evaluation of the water consumption price and its effect on economic and social networks and the environment. The second approach is an evaluation of the water distribution network by TVWPN theory for each urban city in Kuwait. TVWPN theory defines the possible failure scenarios and vulnerability of WDN.

5.2.1. Current Water Price

The water consumption in Kuwait is computed using the current price structure—one block of water consumption represents 1000 IG (4.546 m^3)—which is equal to

$2.837/block ($0.624/m^3). The price variable is one part of water conservation management policy and plays an important role in sustainable development. The SWSIK tool depends on the price variable to show the effects of water demand on the economy, society, and the environment. Based on data from MUC, for each area in Kuwait, the water consumption during January/2011 was used to evaluate the effect of the water price variable on sustainability. Current Scenario involves the current water price, which is evaluated by the SWSIK tool to demonstrate the economic, social, and environment effects.

5.2.2. Water Production Process

In Kuwait, desalination plants have two purposes: 1) to generate electric power and 2) to steam seawater using a multi-stage flashes. There are 6 desalination plants that produce desalinated water to mix with 10% brackish water to have potable water. A water distribution network delivers potable water to reservoirs and then to consumers' households. The total cost of water production depends on the fossil fuels cost (45%) and mechanical cost (55%). Kuwait Oil Company supplies the Ministry of Electricity and Water with fossil fuels at the market price: $104/barrel for oil products, and $2/ Thousand SCF for natural gas (MEW, 2011). The price for fossil fuels is not fixed, it changes daily. In this research, the price for fossil fuels is assumed as annual base given from MEW.

5.2.3. Fuels and energy cost

Oil (Crude oil, gas oil, and heavy fluid oil) and natural gas are the fossil fuels used in the desalination plants in Kuwait. The percentages of each fuel consumed (MJ or BTU) in desalination plants were provided by MOE, as 15.2% crude oil, 8% gas oil, 38.3% heavy fluid oil, and 38.5 % natural gas. Oil products cost $104/barrel and natural gas is $2/Thousand SCF in year 2011. The Multi stage flash method consumes a lot of energy compare to R.O. method to produce a volume of water (Darwish et al., 1989a). The average energy that a desalinating plants needs to produce volume of water is 965.166 BTU/IG (224 MJ/m^3) and the equivalent work is 22 kWh/m^3 (Darwish et al., 2009). The energy cost to produce 1 m^3 of water, as computed from the equation (20) based on the oil price of $104/barrel ($14/GJ or $14.77/M BTU), is approximately $2.6 per m^3.

Energy Cost ($/Vol.) = Power cost ($/barrel or $/kWh) * Energy consumption (MJ/Vol. or kWh/Vol.) (20)

5.2.4. Water cost and government subsidy

The government subsidizes the water price in Kuwait as well as the electricity price. The total cost of water is 45% energy cost and 55% mechanical cost. The total cost of 1m^3 of water is $5.8 while consumers pay $0.624 per m^3. The Ministry of Energy is subsidized the water price by 89.2%.

Total Cost ($/Vol.)= Energy Cost ($/Vol.)+ Mechanical Cost ($/Vol.) (21)

5.2.5. The result of Implementing SWSIK tool

Fossil fuels generate most of Kuwait's national income. The SWSIK tool determined the energy needed to produce water for 78 areas in Kuwait. Water consumption per area was multiplied by the average energy of desalinating plants needed to produce volume of water: 965.166 BTU/IG (224 MJ/m^3). The volume of each fossil fuel consumed can be computed by multiplying the ratio of fossil fuels needed divided by the heat content for each fuel. The properties for each fuel are listed in Appendix 1. Table 14 presents the energy required to produce the water demand for each area under the current water price scenario and the fuel volumes in barrels or MSCF that are used to produce the water demand. Energy content (net calorific value) for crude oil, HFO, and gas oil were assumed to be 5.48 million BTU/barrel (5781.626 MJ/barrel), 5.607 million BTU/barrel (5915.9 MJ/barrel), 5.43 million BTU/barrel (5729.82 MJ/barrel), respectively. While the energy content for natural gas was 1093.33 BTU/SCF (1.15 MJ/SCF), and the data were provided by MEW for the year 2011. Table 14 presents the fuel cost and total cost to produce 626.7 Mm^3 of water for urban areas in Kuwait for year 2011. The total cost is equal to $ 3.614 billion/year, which includes mechanical and energy costs.

$$\text{Energy needed (BTU or MJ)} = \text{Vol. of water} * \text{average energy to produce 1 IG } (1\ m^3) \quad (22)$$

The SWSIK tool analyzed the environmental aspects of the water system in Kuwait by computing the emissions from fossil fuels for the 78 areas in terms of their water consumption. CO_2, NO_2, and SO_2 are the pollutants emitted from fossil fuels and their rates in air were considered in the analysis. Equation 23 determined the rate of pollutants emitted from the consumed fossil fuels (Darwish et al., 2007). The properties of the fossil fuels and the mass balance equations of CO_2, NO_2, and SO_2 can be found in in Appendix A.

$$\text{Emission Rate}_i = (\text{Pollutant content in Fuel})*\left(\frac{MW_{POLLUTANT}}{MW_{FUEL}}\right)*(\rho * \text{Vol. of fuel}) \qquad (23)$$

Fuel cost and total cost per volume of water consumption for each of 78 areas was determined by the SWSIK tool from equations (24) and (21).

$$\text{Cost of Fuel} = \sum_{i=1}^{4}(Vol.of\ fuel\,needed_i * price\ of\ Fossil\ Fuel_i) \qquad (24)$$

Where i= Crude oil, gas oil, HFO, and Natural gas.

Table 14 Energy needed and Total cost of producing freshwater for zone in 2011

Zone	Energy Needed (TJ)	Crude oil (M. bbl)	Gas oil (M. bbl)	HFO (M. bbl)	Natural Gas (M. SCF)	Energy Cost ($ Million)	Total Cost ($ Million)
Z1	42345.44	1.11	0.59	2.74	14133.99	490.65	1090.33
Z2	29365.69	0.77	0.41	1.90	9801.63	340.25	756.12
Z3	16908.44	0.44	0.24	1.09	5643.67	195.91	435.37
Z4	6261.78	0.16	0.09	0.41	2090.05	72.55	161.23
Z5	4954.32	0.13	0.07	0.32	1653.64	57.40	127.57
Z6A	7842.50	0.21	0.11	0.51	2617.66	90.87	201.93
Z6B	8219.24	0.22	0.11	0.53	2743.41	95.23	211.63
Z7	4756.57	0.13	0.07	0.31	1587.64	55.11	122.47
Z1A	17526.39	0.46	0.24	1.13	5849.93	203.07	451.28
Z WAFRA	2205.95	0.06	0.03	0.14	736.30	25.56	56.80

Table 15 Pollutant emission due to water production for zone

Zone	CO_2 [Million M.T]	NO_2 [Thousand M.T]	SO_2 [Thousand M.T]
Z1	3.027	19.773	38.214
Z2	2.099	13.712	26.501
Z3	1.209	7.895	15.259
Z4	0.448	2.924	5.651
Z5	0.354	2.313	4.471
Z6A	0.561	3.662	7.077
Z6B	0.588	3.838	7.417
Z7	0.340	2.221	4.293
Z1A	1.253	8.184	15.816
Z WAFRA	0.158	1.030	1.991

Table 15 gives an indication of the fossil fuels emissions in each zone. The SWSIK tool provides the economic and environment impacts of water consumption under the current water price scenario to give an early warning of the need to change to a new water price policy and reduce the consumption of fossil fuels, especially when 12 % of oil produced in the country is spent in desalination plants.

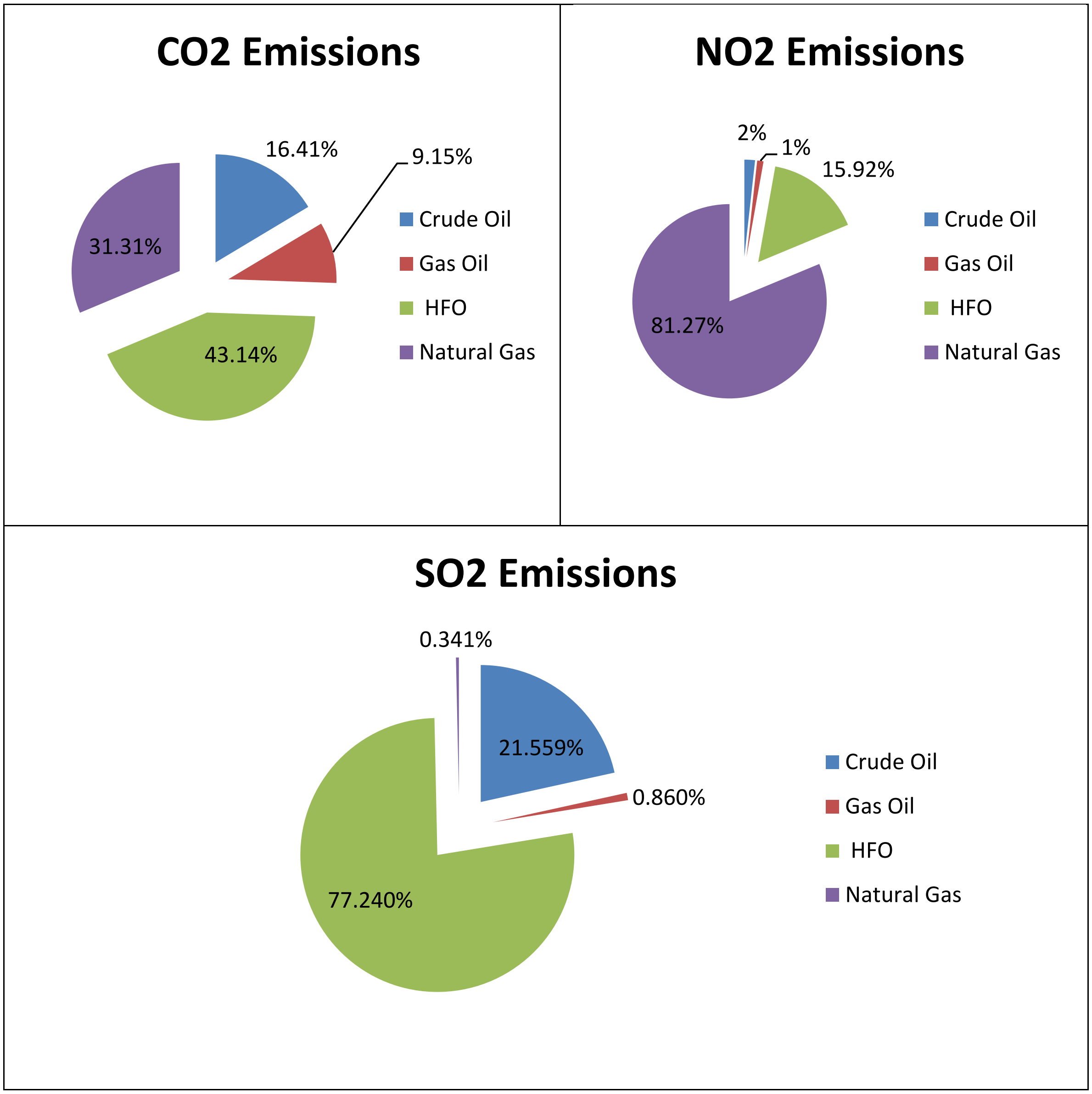


Figure 25 the participate of fossil fuels to emit it each pollutants

The annual revenue from selling freshwater was \$175.98 million in 2011 (MEW, 2011) and that only represents 45 % of the real total price after subsidies (\$391.06 million). The SWSIK tool evaluated the effect of the current water price (\$0.625 per m^3) and indicated that the current subsidy of the total water price is an unsustainable solution and gives almost zero economic value to consumers.

5.3. Calculation of SKI indicators and Final Index value

SKI is comprised of a group of indicators in economic, social, and environment dimensions in terms of a water system. Data used to calculate SKI were collected after MUC simulated the water demand data from the year 2011. SKI index is measured by 16 indicators derived in the methodology. The SKI score is the average of the 4 sub-category scores (resources, infrastructure, capacity, socio-economic). Each subcategory score is computed by dividing the sum of the value indicators by the number of indicators. Results of SKI indicators were analyzed for the 78 areas in Kuwait. An area called Abdullah Al-Mubarak was used as a case study to provide SKI indicator scores and then determine the SKI index value. A sustainability profile was created for Abdullah Al-Mubarak to provide information about area, water facilities, and SKI indicators.

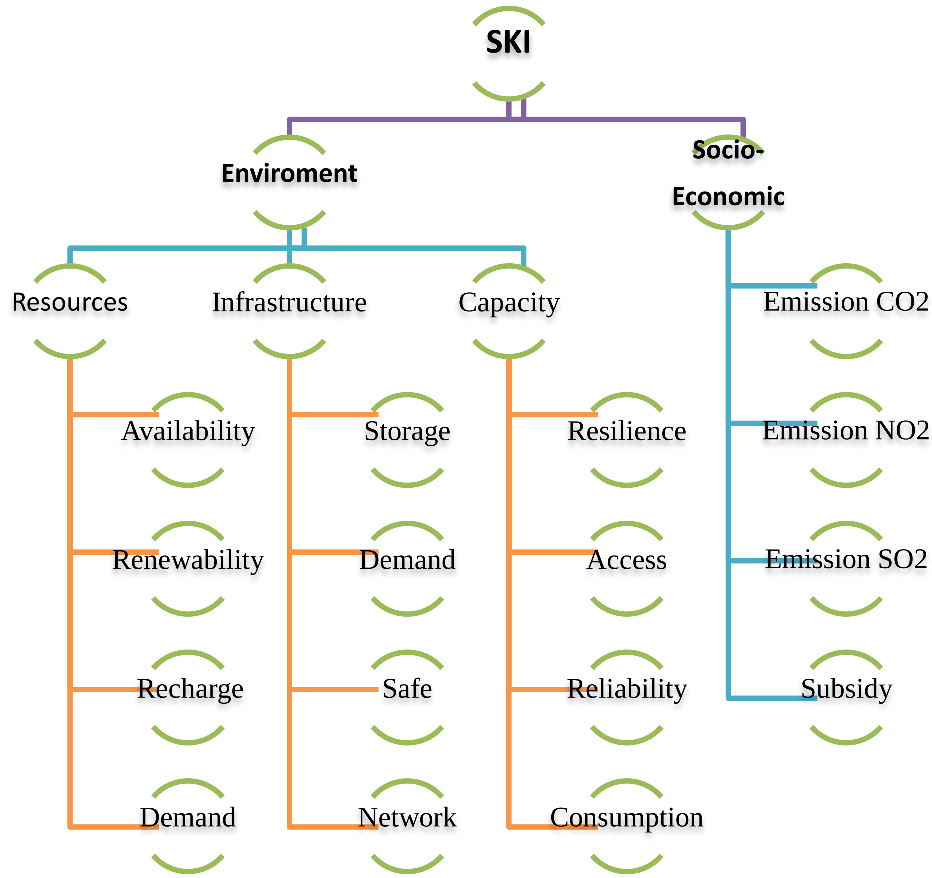


Figure 26 SKI Index Structure

5.3.1. SKI profile for Abdullah Al-Mubarak area

Abdullah Al-Mubarak is a new area close to the new campus of Kuwait University and Kuwait airport. Based on the 2011 data in MUC, the total population was 38,981 and the total numbers of households was 5,643. In Kuwait there are two types of water tower tanks: 1) balancing towers that are used if the demand is low (between 11 pm and 6 am), and 2) storage tower that supply water directly to the community. Abdullah Al-Mubarak area has 8 storage towers (D14) that supply the entire area. Elevated towers (D14) have a total capacity of 5.288 MIG (24.04 thousand m^3). Ground water storage (E

13) is the water source for elevated towers (D14) and the length of main pipeline between them is 27500 m. The SKI indicators and index were determined based on 2011 data from MUC. Water consumption per day was 19,210 m^3 and daily water use per capita in Kuwait was 592 L/d per capita in November 2011.

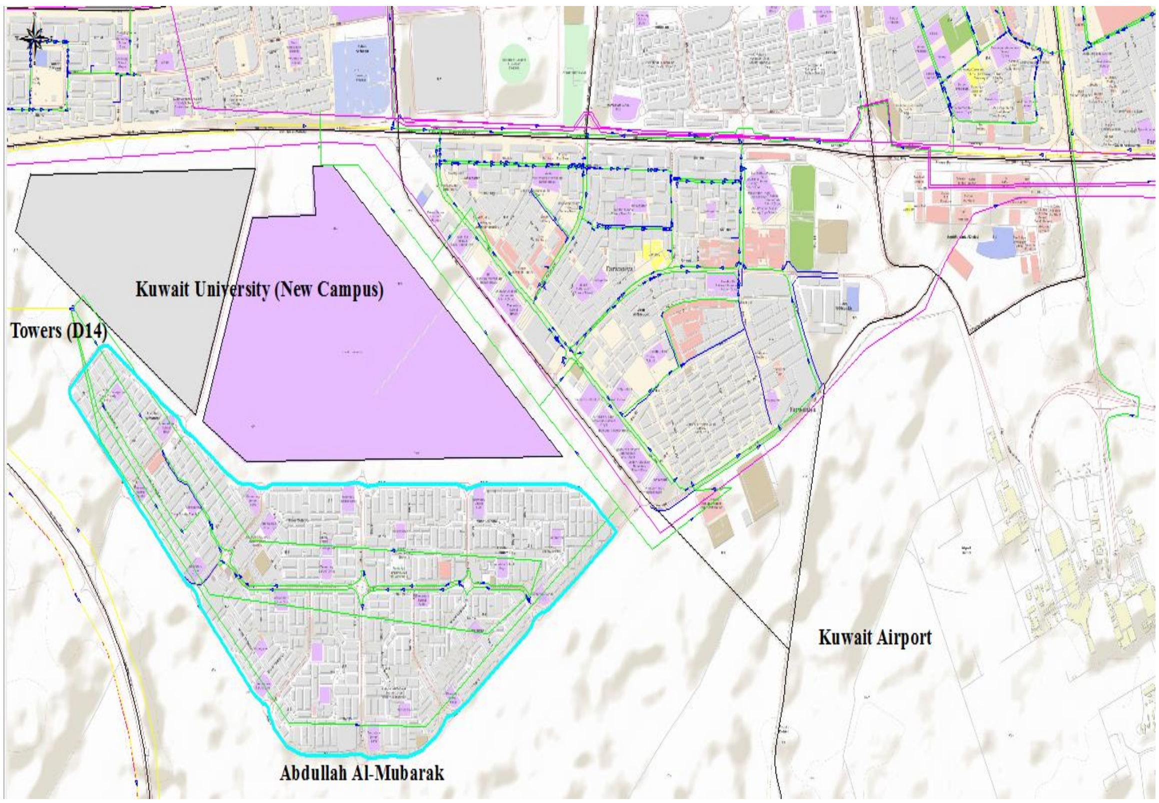


Figure 27 Abdullah Al-Mubarak Location from ArcGIS

Table 16 SKI indicators Scores for Abdullah Al-Mubarak in year 2011

Category	SKI Indicators	Indicator Score (%)	Score (%)
Resources	**Indicator 1:** Availability (R_{av})	11	28
	Indicator 2: Renewability (R_r)	0	
	Indicator 3: Recharge (R_{ASR})	77.42	
	Indicator 4: Demand (R_D)	25	
Infrastructure	**Indicator 5:** Storage (I_s)	32.75	66
	Indicator 6: Demand (I_d)	40	
	Indicator 7: Safe Water (R_{sws})	100	
	Indicator 8: Network (I_N)	90	
Capacity	**Indicator 9:** Resilience (C_{rs})	N/A	72.8
	Indicator 10: Access (C_a)	100	
	Indicator 11: Reliability (C_r)	100	
	Indicator 12: Consumption (C_{Capita})	18.5	
Socio-economic	**Indicator 13:** Emission CO_2 (S_{CO_2})	86.1	62.74
	Indicator 14: Emission SO_2 (S_{SO_2})	89.3	
	Indicator 15: Emission NO_2 (S_{NO_2})	64.8	
	Indicator 16: subsidy (S_S)	10.75	
SKI index			**57.4**

The SKI index score for the Abdullah Al-Mubarak area overall was 57.4 % (see Table 16). Resource indicators have scores at the national (Kuwait) and local levels. *The Availability Indicator* has a value of 11%, indicating the amount that desalination plants can increase the supply. Kuwait has only one conventional renewable water resource, groundwater, which is equal 0.02 Km^3 per year. The *Renewability Indicator* has zero value because it is less than 500 Km^3 per year. The score for *Indicator 3* (*Recharge*) was 77.42%; this is the percentage of recovery efficiency by using ASR as a sustainable water source and long-term supply of freshwater. The standard water per capita assigned by policymakers in Kuwait equals 150 L/d per capita, and the water demand in November 2011, as measured by sensors in pipelines of the Abdullah Al-Mubarak area, was 592 L/d per capita. The value of *Indicator 4 (Demand)* is 25.33%, which is the sustainable demand score for the area. Overall, the Resources Category has a score of 28 % based on the 4 indicators in this subcategory.

The *Storage Indicator* in the Infrastructure category has a value of 32.75 % indicating how long tanks can supply water to the area in case of a shutdown of the desalination plants. The scores for *Indicators 6* and *7* (*Demand* and *Safe Water*) (40 % and 100%, respectively) indicate the sustainable demand score regarding the number of years before the system reaches 100% capacity and water quality, respectively. *Safe Water Indicator* was 100% due to the fact that there were no issues regarding water quality reported. *Indicator 8 (Network)* had a score of 90% based on the type of water network in area. Generally, the Infrastructure score was 66 %, indicating the need to increase the maintainability and management for WDN.

The *Resilience Indicator* designates the system recovery score due to a failure scenario. There is no data for pressure in WDN but by developing MUC, the *Resilience Indicator* can then compute the number of times that the pressure in WDN dropped below the designed peak pressure. In Kuwait, the percentage of access to freshwater is 100% except when there is a critical situation. As result, the score of the *Access Indicator* is 100%. The *Reliability Indicator* has a value of 100% since the water demand is less than the water supplied. 150 L/d per capita is the goal to achieve sustainable consumption per capita. *Indicator 12* (*Consumption*) has a value of 18.5 %, which indicates how far the daily water consumption per capita is from the sustainable goal. The capacity category illustrates the engineering sustainability aspects of the water system. The category index score was 72.8%.

Indicators 13, 14, and *15* (*Emissions*) have values of 86.1%, 89.3%, and 64.8%, respectively, and reflect the pollutants emitted from desalination plants due to water consumption. The score of the *Subsidy Indicator* was 10.75 % indicating the low water price in terms of the cost of water production. The socio-economic index score (62.74%) was relatively small due to the high pollution emissions per capita and the low economic value of water in Kuwait.

5.4. Application of TVWPN to Kuwait water Infrastructure

The TVWPN was defined in the methodology section as a method that analyzes the most vulnerable parts of water infrastructure. Here it applied to each area in Kuwait individually. A case study of the main pipelines of Abdullah Al-Mubarak was analyzed to demonstrate the aspects of TVWPN. The WDN is formed by 6 junctions, 8 main pipes, and 2 storage facilities that supply the area. The pipelines are ductile iron with 0.15 mm roughness (Amiantit, 2011). The hydraulic and geometric values of WDN were obtained from the MUC simulation for January 2011. In Table 17, damage demand values are the nominal pressure for pipelines used in Kuwait. Hydraulic values such as head loss and flow are obtained by running the Infowater application for a certain period.

Table 17 hydraulic and geometric value of Abdullah Al-Mubarak WPN

Pipe	Nodes	Length (m)	Diameter (mm)	Flow (MIG/d)	Head Loss (m)	Damage demand (m)
1	1-2	5202.46	600	2.11	1.17	360
2	2-3	5205.03	600	0.47	0.07	360
3	1-3	25.35	300	5.51	1.25	490
4	6-4	1758.57	400	0.25	0.23	420
5	6-5	1568.18	250	0.19	0.31	540
6	3-6	610.03	600	0.86	0.03	360
7	2-4	2935.29	400	0.58	0.33	420
8	2-5	3488.83	400	0.64	0.42	420

(a) Clustering Process:

The first step in the clustering process is to identify the candidate *WPN branch clusters* for this area. Two or more *leaf clusters* (Pipeline) form the *WPN branch cluster*.

Junctions 1 and 3 are reference clusters. The table (18) shows the initiate candidate *WPN branch clusters* in stage 1 and the factors that effect on the process of TVWPN.

Each candidate has a factor value that is the summation of the factor value of the leaf clusters formed. Since clustering is progressive, the following points illustrate the clustering process:

- The first stage is identifying the candidate WPN branch cluster (table 18).
- According to the vulnerability criteria for clustering (total head loss ΔH_{min}) for all candidates, the WPN branch cluster [6+4] is the first WPN branch cluster, due to low head loss value. Figure 28b shows the first step of the clustering process. The first criteria of clustering, total head loss ΔH_{min}, was enough to identify the new WPN branch cluster in stage 1.
- Again, stage 2 in table 10 is identifying all the candidates for the WPN branch cluster including the new branch cluster 9.
- The second step in the clustering process is selecting a candidate [9+5] to be the WPN branch cluster 10, based on the minimum value of total head loss among other candidates. The new branch cluster 10 is represented in red in figure 28c.
- Stage 3 in table 10 is identifying all the candidates for the WPN branch cluster including the new branch clusters 9 and 10
- The lowest head loss value in stage 3 was a candidate [10+7]. It is selected to be WPN branch cluster 11, and is shown in red in figure 28d.
- Stages 4 and 5 in table 10 are identifying the all candidates for the WPN branch clusters
- First in stage 4, candidate [11+2] is selected to be the WPN branch cluster 12 based on the minimum value of total head loss among other candidates. Then in stage 5, candidate [12+8]

is selected to be the WPN branch cluster 13.Figures 28e and 27f show in red the new branch cluster.

- Stage 6 determined a new branch cluster 14 that was formed from candidate [1+3]. Figure 28g provides branch cluster 13 in blue and recently formed branch cluster 14 in red.
- Branch clusters 13 and 14 are the only candidates in stage 7, so they formed branch cluster 15. Figure 28h represents WDN, excluding water storages.
- At this stage of analysis, there are two storage supply areas. But water storage at junction 3 is dependent upon water storage at junction 1, so the last WPN branch cluster is formed from reference cluster 16 (water storage at junction 1) and branch cluster 15. Figure 28i shows the last WPN branch cluster 17 which is the root cluster of WDN.

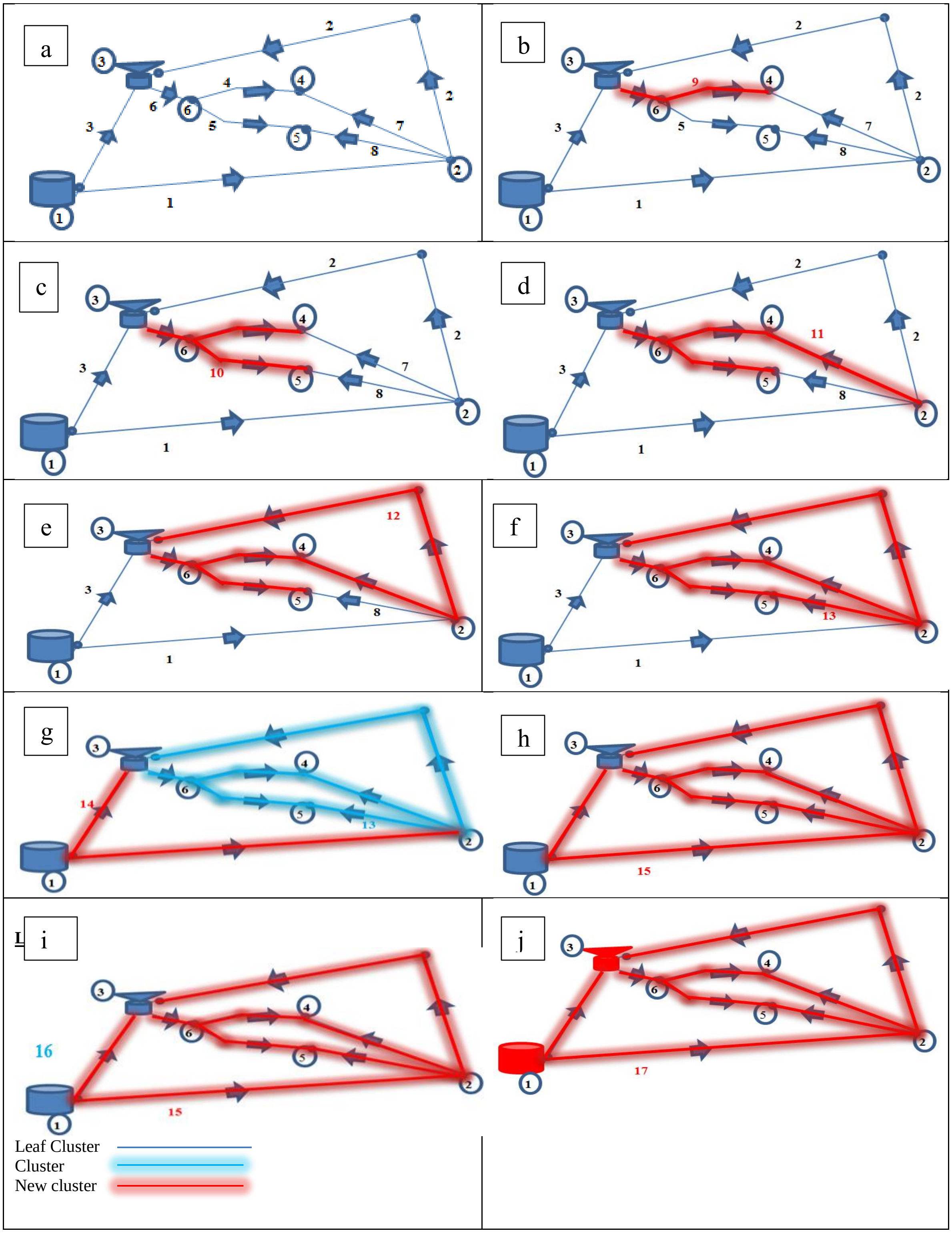


Figure 28 Clustering Process of WPN

Table 18 The process of formed new branch cluster by Clustering Process

Stage	Candidate	ΔH_L (m)	E (m)	η	DSI (m)	New Branch Cluster
1	1+3	2.42	850	5	0	-
	1+2	1.24	720	4	0	-
	6+4	**0.26**	780	4	25.35	**9**
	6+5	0.34	900	4	25.35	-
	4+5	0.54	960	3	635.38	-
	1+8	1.59	780	4	0	-
	1+7	1.5	780	4	0	-
	7+8	0.75	840	4	5202.46	-
	4+7	0.56	840	5	635.38	-
	5+8	0.73	960	5	635.38	-
2	1+3	2.42	850	5	0	
	1+2	1.24	720	4	0	
	9+7	0.59	1200	6	25.35	
	9+5	**0.57**	1320	4	25.35	**10**
	1+8	1.59	780	4	0	
	1+7	1.5	780	4	0	
	7+8	0.75	840	4	5202.46	
	5+8	0.73	960	5	635.38	
3	1+3	2.42	850	5	0	
	1+2	1.24	720	4	0	
	1+8	1.59	780	4	0	
	1+7	1.5	780	4	0	
	10+7	**0.9**	1740	5	25.35	**11**
	10+8	0.99	1740	5	25.35	
4	1+3	2.42	850	5	0	
	1+2	1.24	720	4	0	
	1+8	1.59	780	4	0	
	11+2	**0.97**	2100	3	25.35	**12**
	11+8	1.32	2160	4	25.35	
5	1+3	2.42	850	5	0	
	1+8	1.59	780	4	0	
	12+8	**1.39**	2520	2	25.35	**13**
	12+1	2.14	2460	1	0	
6	1+3	**2.42**	850	5	0	**14**
	13+1	2.59	2880	1	0	
7	**13+14**	**3.81**	**3370**	**0**	**0**	**15**
8	15+16	-	-	-	0	**17**

(b) Hierarchical Model:

The clustering process is represented in a graphical way called a Hierarchical Model. The starting point to understanding the hierarchical model is from bottom to top. Figure 29 illustrates the Hierarchical Model of Abdullah Al-Mubarak WPN.

The Hierarchical model for WPN was drawn based on the information obtained during the clustering process stages. Understanding the hierarchical model in figure 29 should begin from the bottom of the model which represents all *leaf clusters*. Next, each upper level represents new branch clusters that formed from the two leaf clusters. The top of the hierarchical model is the root cluster that includes the WDN branch cluster and the reference cluster (water storage at junctions 1).

(c) Unzipping Process:

The most vulnerable part of WPN can be found by an unzipping process and by using the Hierarchical Model. The criteria of unzipping applied from the top moving down to search the part properly can be damaged in WPN.

Based on the hierarchical model in Figure 29, searching for a vulnerable failure scenario was achieved by applying the unzipping criteria that were mentioned in the methodology. The following procedure illustrates the unzipping process step by step (figure 29):

- ❖ Root Cluster 17 has two WPN branch clusters, 15 and 16. The WPN branch cluster is eliminated if it is a reference cluster (N_R), then WPN branch cluster 15 is selected.

- Moving down in the hierarchical model, branch cluster 15 was formed from branch clusters 13 and 14.
- Based on criteria 2 of the unzipping process—connects directly to the Reference Cluster (CD)—branch cluster 14 was formed from leaf clusters 3 and 1 and both of them do connect to the reference cluster (water storage at junction 1). So the path of branch cluster 14 satisfies this condition and is selected to move down to look at the vulnerable pipe in WDN.
- The candidates to be properly damaged are leaf clusters 1 and 3. By applying the unzipping criteria that have been mentioned in the methodology of TVWPN, leaf cluster 3 has a higher value of head loss. So it is selected to be a vulnerable part in WPN, as the Abdullah Al-Mubarak area will not have enough water if leaf cluster 3 fails. Cluster 3 is connected directly with the elevated tower and has a high flow to supply, proving that cluster 3 is the most vulnerable part in WPN.

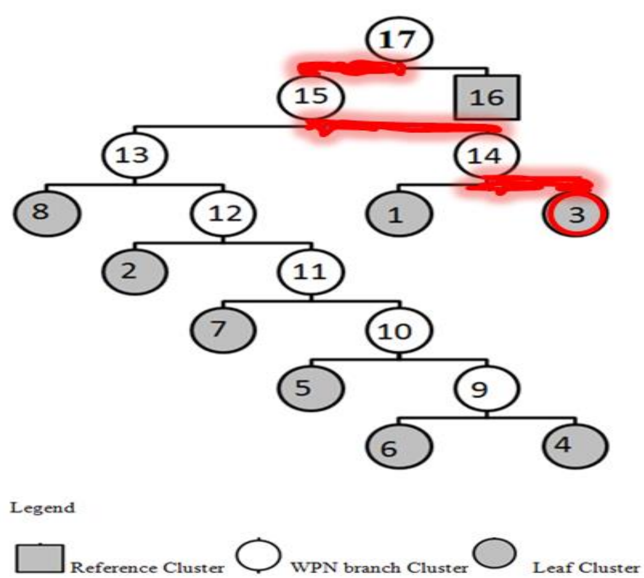


Figure 29 Hierarchical and Unzipping process model of the WPN

5.5. Water Demand Models Results

A number of simulations analyzing two scenarios were performed to analyze a new water price schedule in Kuwait. The first scenario involves a constant price at a range of \$0.6-2.6 per m^3. The second scenario involves providing a quantity of freshwater to consumers free of charge and any consumption over the free allowance is charged at a constant price. The following figure illustrates the second scenario for the price schedule. For example if the free allowance was 150 L per capita per day, then the policymakers have the option to select a unit price between \$0.6- 2.6 per m^3.

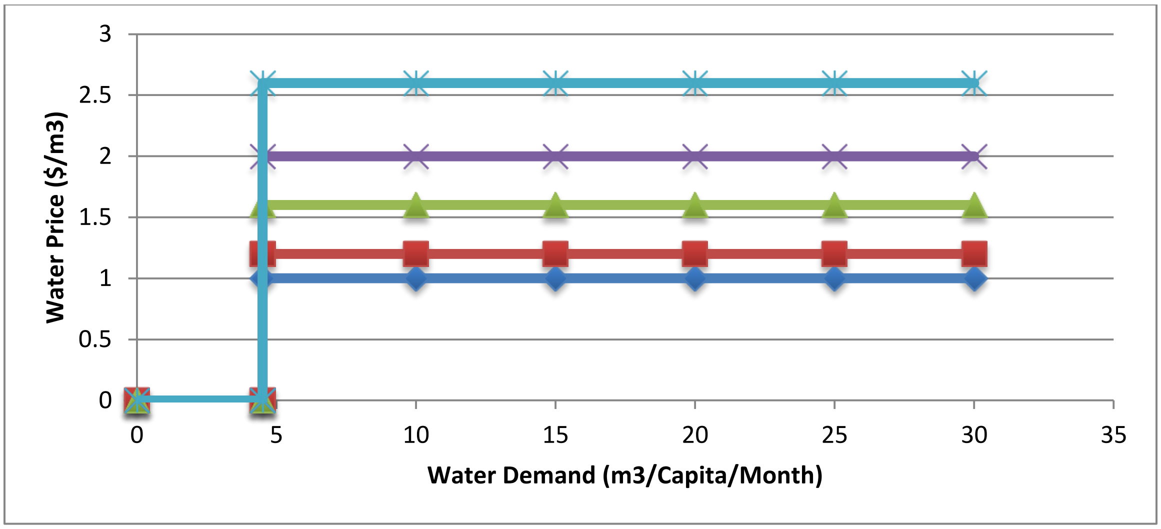


Figure 30 The second scenario for price proposal (150 L/Capita/Day free allowances followed by a fixed price per m^3)

The models of Tunisia and Saudi Arabia were selected due to their common traditions and cultures with Kuwait. Saudi Arabia Model (SA) provides two approaches. The first approach is used when applying a new water price policy for the first time without a non-water price policy. The second approach is used after the consumption behavior has changed and with a well established non-water price policy.

I. First scenario: Constant Price

Water Consumption is priced for each 1 m^3. Figure 31 shows water usage per capita based on the first scenario at different water prices. In the SA model, water price has a real impact to reduce water consumption between \$0.8 and 2.6 per m^3. The purpose of this study is to reduce water consumption by 30 - 40 % to diminish the wastefulness in water consumption. Based on figure 31, it looks more reasonable when water costs are between \$1.0 and \$1.2 per m^3; then the demand will be close to 321 L/C/Day and 279 L/C/Day, respectively. So the reduction based on constant water price that between \$ 1.0 - 1.2 per m^3 would be between 30-40% of the measured water consumption in 2011. The Tunisia model provides almost the same value of water usage in the first scenario even with a different structural model. The SA 2 model is more effective than the previous models due to the role the non-water price has in reducing consumption. Previous study was conducted in California maintained that the non-water price policies will have an impact on curbing water consumption between 4% and 20% in arid and semi-arid countries (Renwick and Green, 1999). Then in the SA 2 model the water price coefficient (Cprice) was decreased to provide more than a 5% reduction in water consumption. The reduction in the SA 2 model is 44 % (261 L/Capita per day) at \$ 1.2 per m^3, if there are non-water price polices, such as encouraging consumers in the media to save water and the distribution of efficient devices. Overall, the three models show the same structure of current water price in Kuwait (\$ 0.624 per m^3), in which water consumption is charged at a constant price: when the water price is increased this indicates greater economic value of the water and the water consumption is decreased. The role of non-water price polices has been inserted in the SA 2 model.

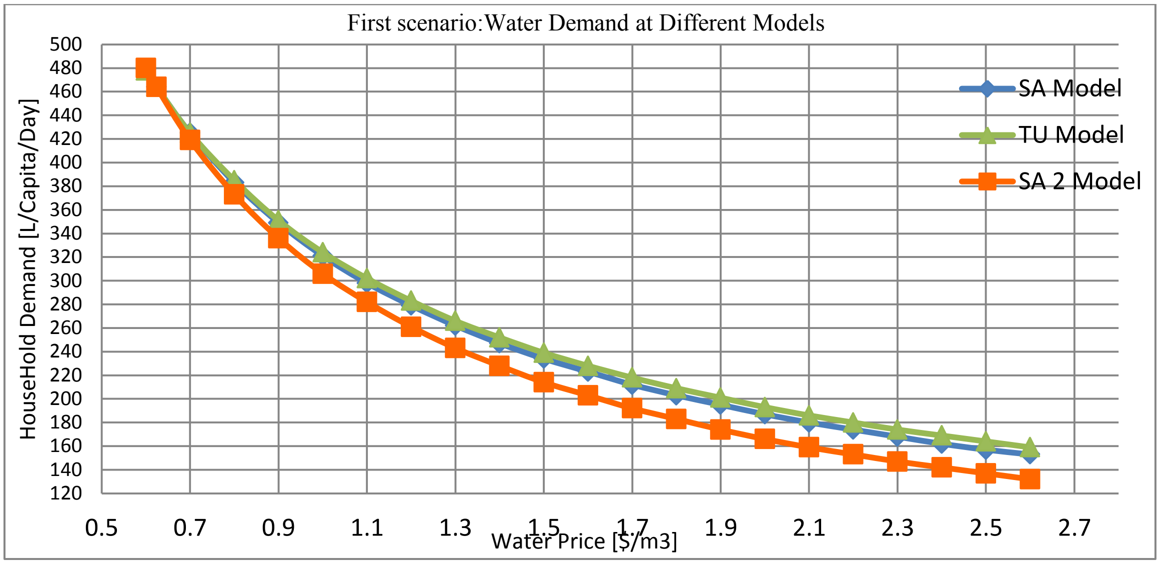


Figure 31 The water consumption per capita for three water demand models in first scenario

The elasticities of the water demand models were determined when water prices change. Elasticity was determined from equation 25. The elasticities for the SA model and the TU model were -0.78 and -.0.75, respectively.

$$\text{Elasticity } (\underline{E}) = \frac{d\ \ln(Q)}{d\ \ln(P_{water})} \tag{25}$$

Where; Q: water consumption and P_{water}: water price

Table 19 shows the elasticity and the reduction of water consumption that can be achieved if the first scenario is adopted of applying a constant water price and collect water bills are collected effectively by installing smart water meters in houses. Replacing all water meters in Kuwait with prepaid water meters will help consumers pay their water bills and let MEW monitor water consumption by connecting devices to a GIS system.

Table 19 Elasticity and Reduction due to apply the first scenario

Elasticity and Reduction due to apply Constant Water Price						
Price	SA Model		Tunisia Model		SA 2 Model	
	Elasticity	Reduction (%)	Elasticity	Reduction (%)	Elasticity	Reduction (%)
0.8	-0.83	17	-0.79	17	-0.93	20
0.9	-0.84	25	-0.83	24	-0.94	28
1	-0.84	31	-0.80	30	-0.94	34
1.1	-0.82	36	-0.77	35	-0.90	39
1.2	-0.79	40	-0.78	39	-0.93	44
1.3	-0.82	44	-0.81	43	-0.93	48
1.4	-0.83	47	-0.76	46	-0.89	51
1.5	-0.81	50	-0.79	48	-0.95	54
1.6	-0.77	52	-0.75	51	-0.84	56
1.7	-0.86	54	-0.76	53	-0.95	59
1.8	-0.78	56	-0.76	55	-0.86	61
1.9	-0.76	58	-0.74	57	-0.96	63
2	-0.84	60	-0.81	58	-0.94	64
2.1	-0.80	61	-0.78	60	-0.90	66
2.2	-0.75	63	-0.72	61	-0.85	67
2.3	-0.81	64	-0.78	63	-0.92	68
2.4	-0.87	65	-0.70	64	-0.83	69
2.5	-0.78	66	-0.75	65	-0.90	70
2.6	-0.67	67	-0.81	66	-0.97	72

In the SA model, the monthly government subsidies dropped to \$170.5 million after applying \$1.0 per m^3 as water price. This will reduce government subsidies by 36%, which will save almost \$95.5 million per month to the government budget.

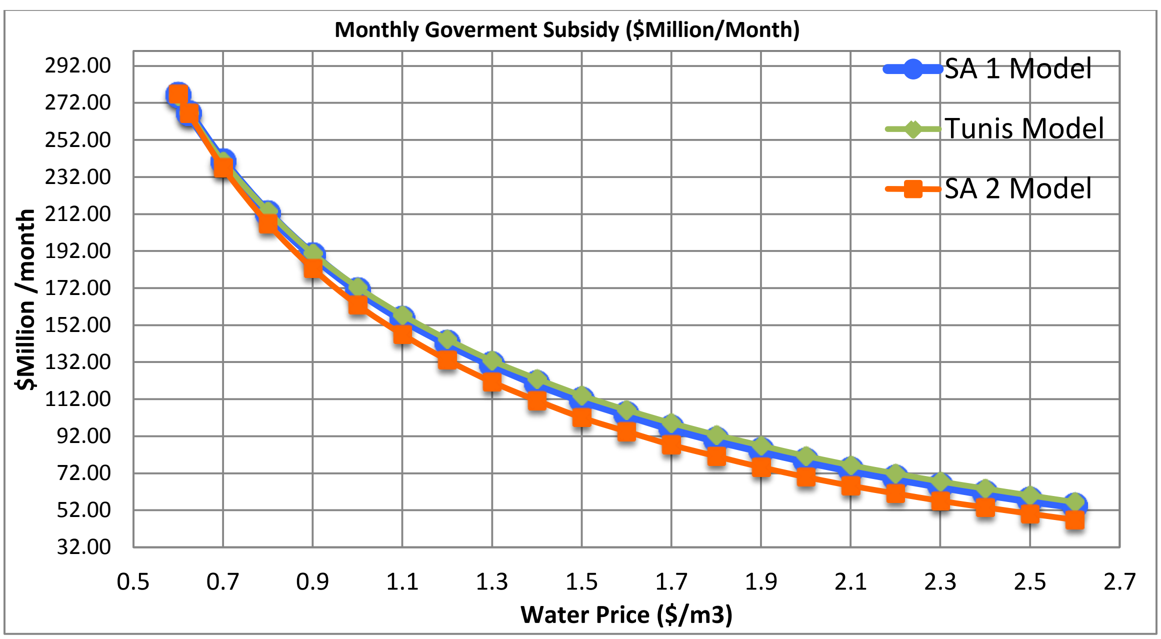


Figure 32 Monthly Government subsidies

II. Second Scenario: Free allowance followed by various pricing schemes

A pricing schedule is proposed that includes free allowance (e.g. 100, 150, 200, or 250 L/Capita/Day), followed by constant water charge (between \$0.6-3.5 per m^3). This scenario would be more acceptable economically for both policymakers and consumers. Fundamentally, if consumers consume water more reasonably, then the government will provide water for free. However, any wasteful water consumption beyond the standard consumption should be charged at a certain constant price. In this scenario, water price was charged by an average price (AP)

$$AP = \frac{[APM * P_{APM}] + [(Q - APM) * P]}{Q} \qquad (25)$$

Where **Q**= Water demand at Constant price + APM [L/c/day]

APM= the allowance of water with free of Charge [L/c/day]

P= water price between [\$0.6- 3.5 per m^3]

$\mathbf{P_{APM}}$= Zero price for free allowance [\$ 0 per m^3]

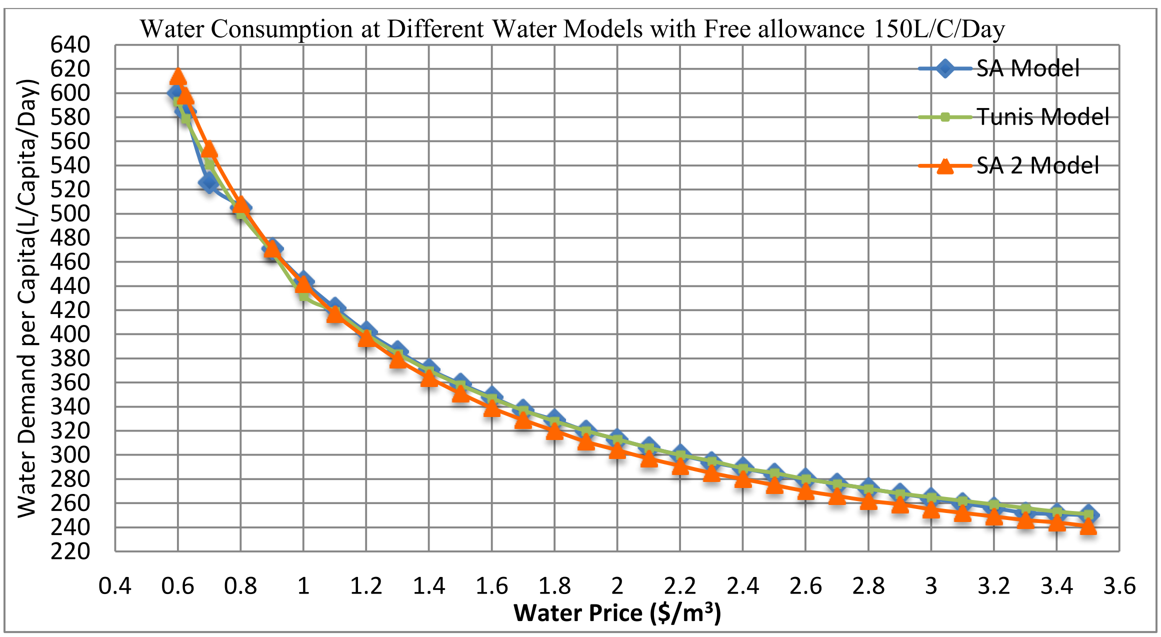


Figure 33 The Water Consumption due to second scenario with free allowance 150 L/C/Day

This scenario limits water consumption per household to be close to the daily quantity of water that is free of charge for consumers. Figure 33 shows water demand with 150 L/Capita/Day free allowances at different water prices. For example water price at 1.6 per m^3 in the SA and TU models with 150 L/Capita/Day shows Water consumptions are 348 and 347 L/Capita/Day, respectively. Table 20 and 21 illustrate elasticity and reduction as a result of the second scenario with 150 L/C/Day free allowances. Water consumption is reduced 25% when the government gives 150 L/Capita/day free of charge and applies \$1.6 per m^3 for excess over the free allowance. The SA 2 model provides a 27% reduction in water consumption with the aid of non-water price policies.

Table 20 The Elasticity and average water price for second scenario

Price	SA Model (150L)		Tunisia Model (150L)		SA 2 Model (150L)	
	A. Price (\$/m^3)	Elasticity	A. Price (\$/m^3)	Elasticity	A. Price (\$/m^3)	Elasticity
0.6	0.44	0	0.43	0	0.44	0
0.624	0.45	-0.92	0.44	-0.80	0.46	-0.97
0.7	0.50	-1.21	0.48	-0.80	0.50	-0.89
0.8	0.55	-0.42	0.54	-0.82	0.55	-0.92
0.9	0.60	-0.83	0.58	-0.80	0.60	-0.93
1	0.65	-0.80	0.65	-0.80	0.65	-0.89
1.1	0.69	-0.78	0.67	-0.82	0.69	-0.92
1.2	0.73	-0.83	0.71	-0.80	0.73	-0.87
1.3	0.78	-0.76	0.75	-0.78	0.77	-0.91
1.4	0.81	-0.82	0.79	-0.78	0.81	-0.88
1.5	0.85	-0.74	0.83	-0.75	0.84	-0.86
1.6	0.89	-0.76	0.86	-0.78	0.88	-0.90
1.7	0.92	-0.85	0.90	-0.79	0.91	-0.84
1.8	0.96	-0.69	0.93	-0.79	0.94	-0.83
1.9	0.99	-0.85	0.96	-0.77	0.97	-0.93
2	1.02	-0.72	0.99	-0.74	1.00	-0.80
2.1	1.05	-0.78	1.02	-0.80	1.03	-0.87
2.2	1.08	-0.73	1.05	-0.75	1.05	-0.81
2.3	1.11	-0.79	1.07	-0.67	1.08	-0.88
2.4	1.14	-0.71	1.10	-0.88	1.10	-0.79
2.5	1.16	-0.76	1.12	-0.63	1.13	-0.75
2.6	1.19	-0.66	1.15	-0.84	1.15	-1.06

Table 21 Reduction due to apply 150 L free allowance followed by constant price

Price	SA Model (150L)		Tunisia Model (150L)		SA 2 Model (150L)	
	Q (L/C/Day)	Reduction %	Q (L/C/Day)	% Reduction	Q (L/C/Day)	Reduction
1	444	4	432	7	442	5
1.1	422	9	419	10	417	10
1.2	402	13	400	14	397	14
1.3	386	17	384	17	379	18
1.4	371	20	370	20	364	22
1.5	359	23	358	23	351	24
1.6	348	25	347	25	339	27
1.7	337	27	337	27	329	29
1.8	329	29	328	29	320	31
1.9	320	31	320	31	311	33
2	313	33	313	33	304	34
2.1	306	34	306	34	297	36
2.2	300	35	300	35	291	37
2.3	294	37	295	36	285	39
2.4	289	38	289	38	280	40
2.5	284	39	285	39	275	41
2.6	280	40	280	40	270	42
2.7	276	41	276	41	266	43
2.8	272	41	272	41	262	44
2.9	268	42	268	42	259	44
3	264	43	265	43	255	45
3.1	260	44	262	44	252	46
3.2	256	45	259	44	249	46
3.3	252	46	256	45	246	47
3.4	251	46	253	45	244	47
3.5	250	46	251	46	241	48

As a result of applying 150 L/Capita/day free of charge followed by \$ 1.6 per m^3, figure 34 shows the government will save around \$ 77.96 million per month based on the SA and TU models. This 29 % reduction in monthly government subsidies can be beneficial for developing the water infrastructure. Overall, government subsidies give zero economic value for a water product at the current water price, while the second scenario contains two variables that are free allowance and reasonable water price over free allowance.

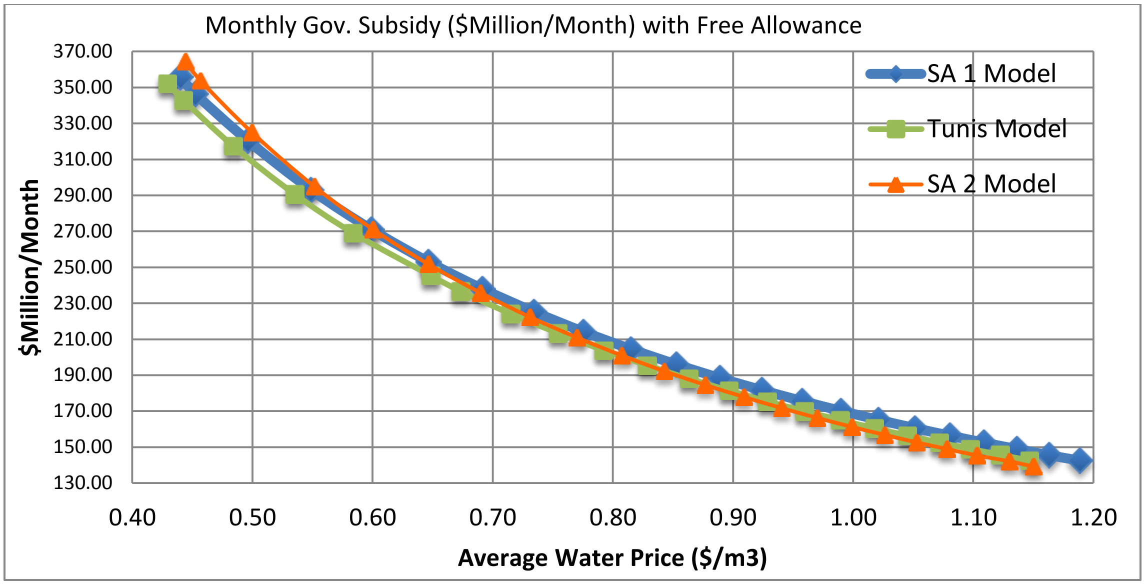


Figure 34 Monthly Government Subsidy due to apply 2nd scenario with 150 L free Allowance

Figure 35 shows how policymakers might select between water price and free allowance to gain a certain reduction in water consumption. This figure shows how much water consumption would be reduced by the government's changing the water price and the free allowance amount.

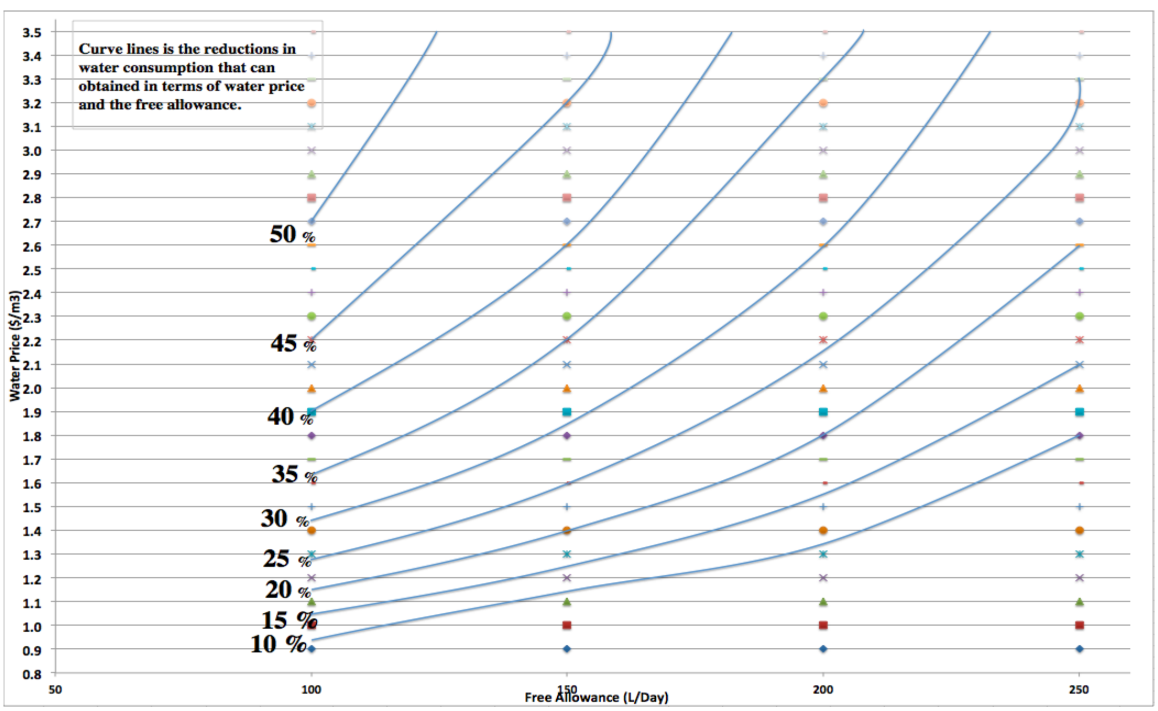


Figure 35 Reductions due to different free allowances

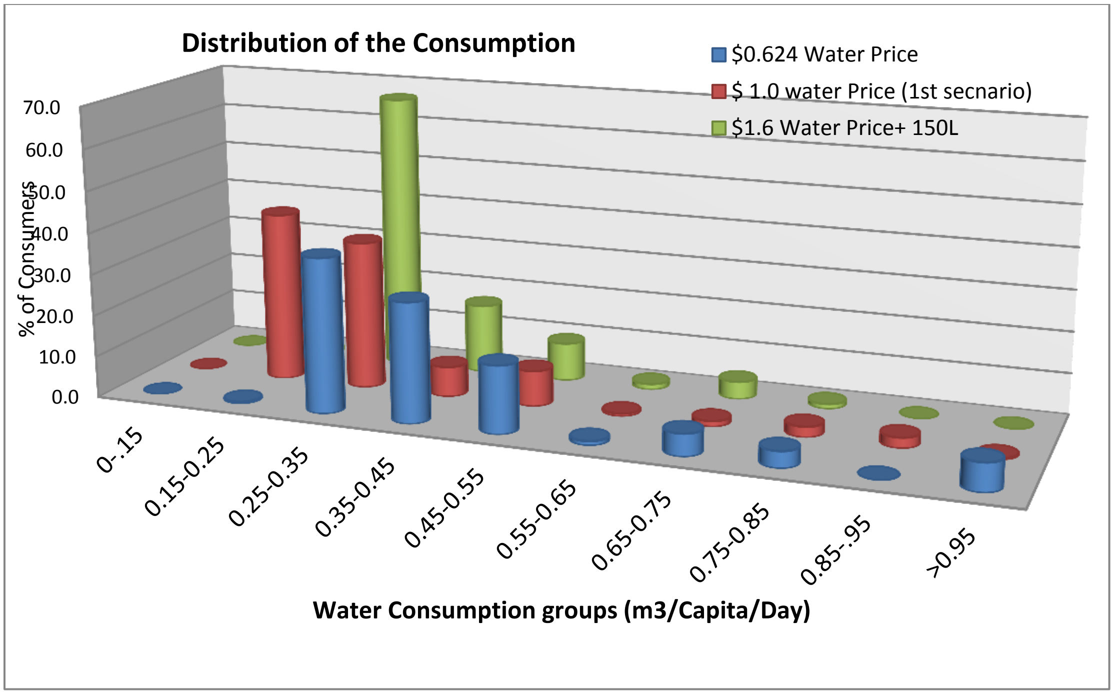


Figure 36 Distribution of water consumption groups using SA Model

As result, the sustainable water price in 1st scenario that charges \$ 1.0 per m^3. On the other hand, 150 L/c/day free allowances followed by constant price \$ 1.6 per m^3 is the sustainable water price that achieved the goal that it reduces (or even limits) water consumption. In figure 36, the distribution of the population under the current water price shows that water consumption is mainly between 250 and 1250 L/day. By applying the first scenario, water consumption was shifted to be less than 450 L/day due to the dramatic increase in water price. In the second scenario, 150 L of free allowance followed by \$1.6 water price, clusters water consumption in the range of 250L to 350L. Generally, the second scenario eliminates wasteful water consumption without leading to a shortage. In addition, it also provides water for consumers free of charge to meet their necessary requirement in life, which is acceptable for both policymakers and consumers. This scenario will encourage consumers to be under the level of free allowance set by the government. In addition, this scenario supports the idea of sustainable consumption, which consumes water without leading to environmental and economic impacts.

5.6. Sustainable water price and consumption

A comparison of the first scenario with the second scenario shows that the latter could be implemented in Kuwait and would be acceptable for the government, especially because it would reduce wasteful water consumption. First, in this section, the growth of water consumption during 2013-2017 is illustrated under both scenarios. Then there is a comparison of the water consumption growth with the installed capacity of desalination plants in Kuwait. Finally SWSIK and SKI are applied to the first and second scenarios to show the improvements in the sustainability status.

When you compare water consumption per capita per day for Kuwait (464 L) with countries such as Germany (139 L), Finland (150 L), Belgium (110 L), Denmark (131 L), Netherlands (127.5 L), Spain (280 L), and England (150 L), it is evident that there is a need to reform the water price policy to reduce consumption (Environment Agency, 2008). Kuwait depends almost entirely on using oil to produce freshwater from desalinated seawater. In addition, oil production is the main source of income in Kuwait. Figure 37 shows the projection of the water consumption under the following scenarios between 2013 – 2017: 1) Current scenario is \$0.624 per m^3, 2) First scenario is \$ 1.0 per m^3, and 3) Second scenario is free allowance (150 L/C/day) followed by \$1.6/m^3.

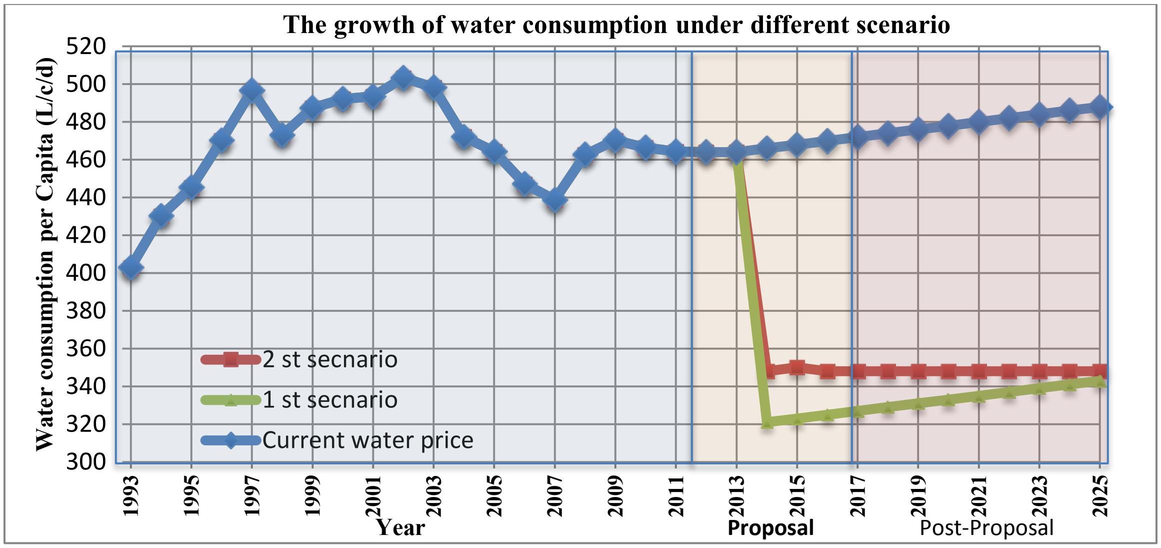


Figure 37 Water consumption growth under 3 different scenarios

A shortage will occur if the current consumption behavior continues. After a couple of years the demand for water will be greater than the water supply produced from desalination plants. Regarding this situation, the Kuwait government has to deal with this issue by either 1) constructing new desalination plants to meet the growth of water consumption, which means increasing the use of oil in desalination plants, increasing government subsidies, and increasing environmental pollution; or 2) reforming the water price policy to reduce the overconsumption of water. Comparing the current water price with the two proposed scenarios shows when the deficit or shortage will happen under the current installed capacity for 6 desalination plants in Kuwait (Figure 38).

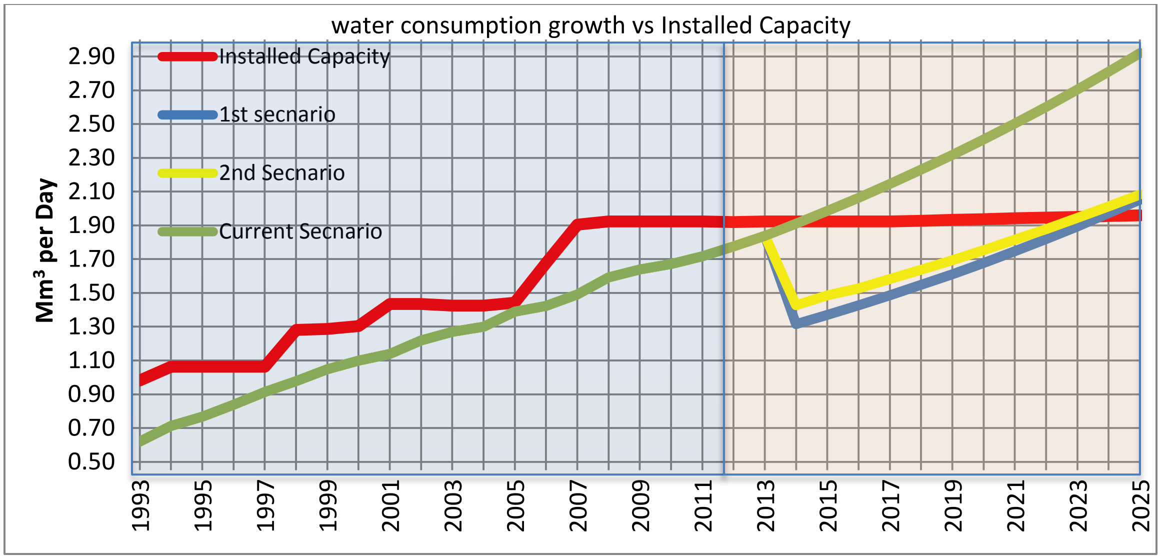


Figure 38 The growth of water consumption based on different scenarios with installed capacity

A shortage will occur in 2014 if the Kuwait government does not change the water price structure. The current water price (\$0.624 per m^3) gives zero economic value to consumers. As a consequence, water bills will not be collected effectively due to the low cost and dramatic increase in water consumption. The first scenario, which charges \$1 per m^3, might not be acceptable for consumers due to the stigma associated with increasing prices. However, it will postpone the need to increase the capacity of desalination plants until 2124. On the other hand, the role of the government is to provide vital necessities for the population. As such, the second scenario provides a free water allowance, followed by a constant price for water used above the allowance. This option allows consumers to control their consumption and remain below the free allowance limit. Since 150 L/capita/day is an ideal standard, the free allowance policy appears to be the most sustainable option followed by \$1.6 per m^3. The second scenario will postpone the need for new desalination plants until 2023. Overall, both scenarios will postpone the shortage situation at least 10 years. During this time, the government can construct new desalination plants that are dependent on newer sources of energy, such as solar energy.

5.6.1. Application of SWSIK to the proposed water price scenarios

SWSIK provides an environmental and economic analysis of the water demand volume. As mentioned in Figure 17, the procedure for determining the environmental impact, the energy needed, and the total cost of production depends on the total volume of water. Here, three scenarios were evaluated by SWSIK to show the effects of the water price policy in Kuwait. Then, the same procedure is applied to urban areas in Kuwait. The time frame to show the effect of the water price proposal is from 2008-2017. The first five-years (2008-2012) are based on the current water price (\$0.624 per m^3). SWSIK analyzes three scenarios based on the following:

- Current scenario: continue on the same water price during 2013-2017.
- First scenario: increase water price to \$1.0 per m^3 during 2013-2017.
- Second scenario: free allowance (150 L/C/day) followed by \$1.6/m^3 (2013-2017).

Since the proposed water price scenarios is not implemented in the first 5 years (2008-2012), all three scenarios have the same total water consumption for the first 5 years (2008-2012). The first year (2013) of water price proposal assumes no change in water consumption per capita per day from the previous year. Population growth in Kuwait is assumed almost 3.5% every year.

The current water price scenario is assumed to continue with the same water consumption per capita (464 L/C/day) during 2014-2017. The total volume of water consumption will exceed the total volume of installed capacity for the 6 desalination plants at the end of 2014. However, SWSIK evaluated water consumption after 2014 to show the economic and environmental results for the current water price (\$0.624 per m^3).

The first scenario is a constant price that applies \$1 for each m^3. By using the SA model to determine water consumption at this constant price, the first scenario is assumed to change water consumption after each year of implementation. Water consumption is 321 L/C/day, due to the increased water price to \$1 per m^3, and installed smart water meters will let consumers monitor and pay their water consumption wirelessly. After 2014, it was assumed based on SA model that the water consumption per capita is 321 L/C/day, due to first scenario's (\$1.0 per m^3) increase by +2 L every year.

The second scenario offers a new water price structure in Kuwait. It encourages consumers to consume water more wisely, and then they will not need to pay water bills. 150 L/capita/day is the free allowance and any consumption over that is priced by \$1.6 per m^3. The SA model shows water consumption will drop to 347 L/C/day in the second year after implementing second scenario. Water consumption in the last three years of the water price proposal increases by +2 L/C/day from the preceding year. SWSIK analyzed water consumption for 2008-2017 under the three water price scenarios to show the energy that is needed from fossil fuels, the environmental impact, and the total production costs. It was assumed that the percentage of fossil fuels used for the proposal period is the same as in year 2012. Table 22 shows the percentage of fossil fuels used in desalination plants. Applying the first scenario (\$1.0 per m^3), the Kuwait government will save almost 5 million barrels per year from oil products (crude oil, gas oil, and HFO) and reduce natural gas usage by 31%. On the other hand, the second scenario can reduce the usage of oil products and natural gas in desalination plants by 26% from the current scenario during the proposal period.

Table 22 % Fossil Fuels usage in Desalination Plants

Year	Crude oil %	Gas oil %	HFO %	Natural Gas &
2008	8.4	5.7	58.4	27.5
2009	18.2	8.1	47	26.7
2010	15.5	8.1	42.9	33.5
2011	15.2	8	38.3	38.5
2012	14.3	3	40.8	41.9
2013-2017	14.3	3	40.8	41.9

SWSIK evaluated the economic aspects of the three scenarios. The total cost of annual water production in the year 2017 will be \$4.4 billion under current water price scenario. The first and second scenarios are going to save \$1.35 and \$1.15 billion/year, respectively. Both scenarios show that they can eliminate wasteful water consumption. As a consequence of eliminating water overconsumption will reduce fossil fuel usage in desalination plants. Therefore, the GDP per capita in Kuwait can increase due to the reduction of fossil fuel usage. The percentage of fuel consumed in desalination plants to generate water out of the total fuels consumed in all sectors is equivalent to 12% (Darwish et al., 2008). By applying either the first or second scenario, the percentage of fossil fuels consumed in desalination plants out of the total fuels consumed in all sectors will drop to 8.8%. Figure 39 demonstrates the projection for oil products and natural gas under 3 different scenarios between 2013 and 2017. It indicates that both scenarios have the potential to reduce oil products and natural gas.

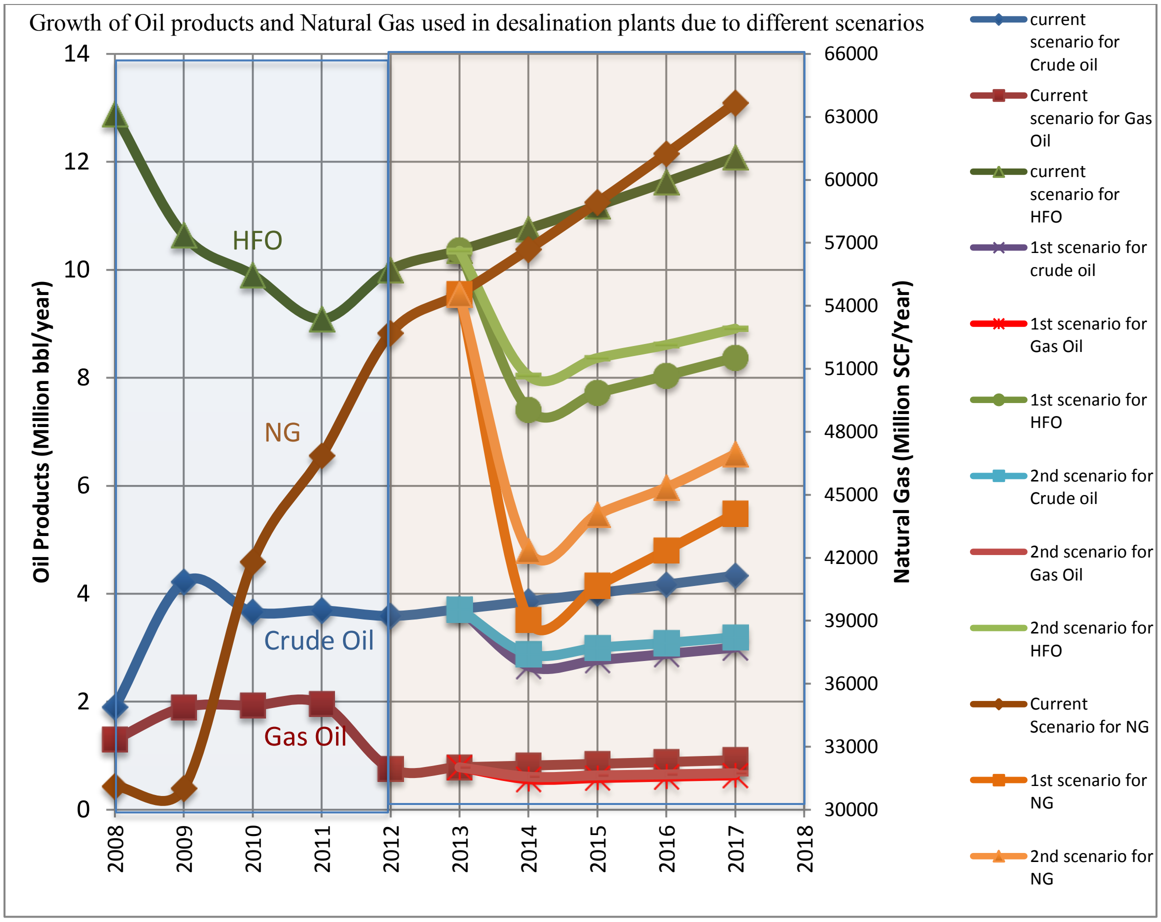


Figure 39 The growth of Oil production under 3 scenarios for water price policy

Figure 40 illustrates the environmental impacts resulting from the application of the three different scenarios for water price structure. SWSIK determined CO_2, SO_2, and NO_2 emissions under the first and second scenarios and compared the results with the current scenario in proposal period 2013 to 2017. The first scenario reduces CO_2 emissions up to 3.5 million Metric Tons, compared to the CO_2 emissions under the current scenario, and the reduction in CO_2 emissions under second scenario is 26%. The values of the mass reduction in NO_2 and SO_2 emissions are almost the same in the first and second scenarios.

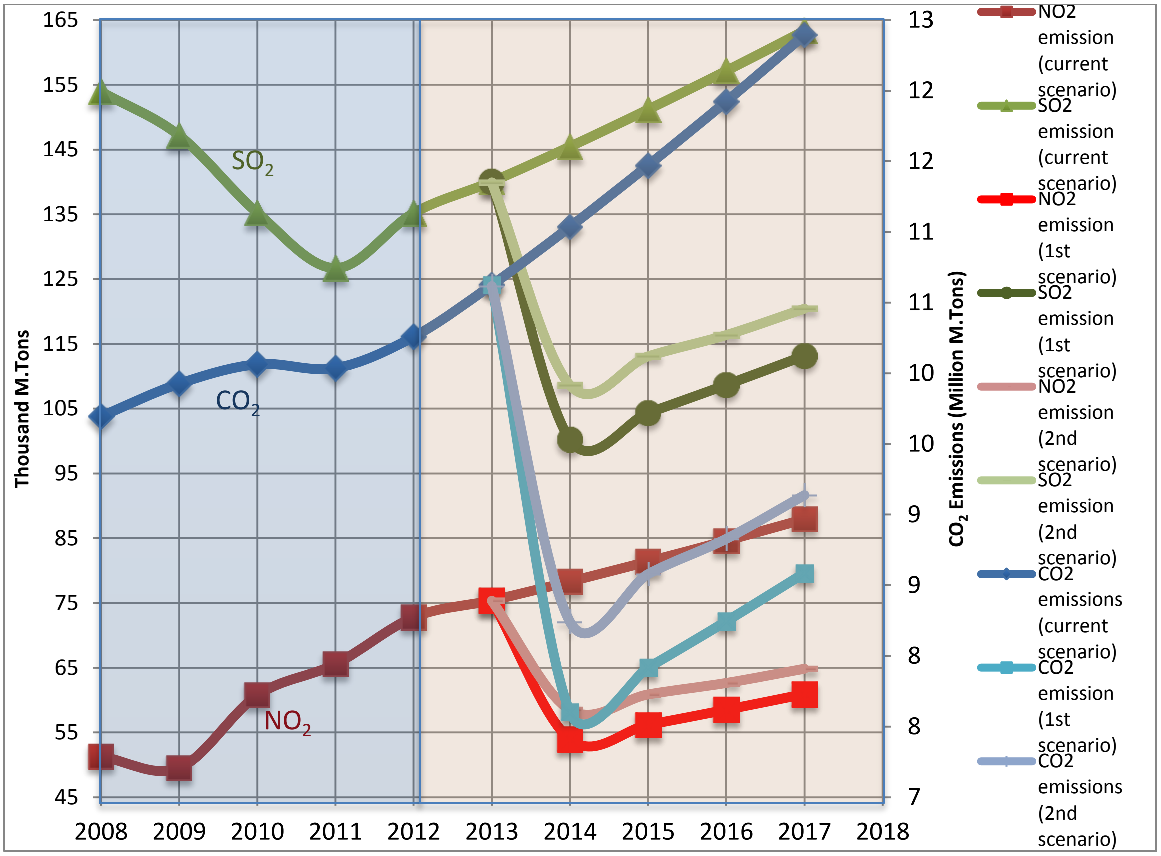


Figure 40 The emissions of CO_2, NO_2, and SO_2 under 3 scenarios for water price policy

Overall, SWSIK provides a comprehensive analysis that measures the environmental and economic aspects resulting from the implementation of a new water price schedule. Although the first scenario can reduce energy costs and pollution, the second scenario is more acceptable for consumers and policymakers, as it satisfies the sustainability conditions, which are: 1) save the environment, 2) reduce costs, 3) be acceptable to society, and 4) achieve policymakers' goals.

5.6.2. SKI results for the proposal of water price scenarios in Kuwait

SKI indicators test the movement forward of the ideal values of sustainability. The structure of SKI includes resources, infrastructure, capacity, and socioeconomic categories. Sixteen indicators were classified into 4 categories that represent SKI indicators. SKI index is the average of the 4 categories. The proposal scenarios were evaluated during 2013-2017 to show the benefits of reducing wasteful water consumption and saving oil products in Kuwait. The scores of the SKI index were determined for urban areas in Kuwait under the three scenarios for water price policy (current water price, first scenario, second scenario). In the second year, after implementing both proposal scenarios, the SKI score for all urban areas (78 areas) increased by 10% to 20% from the previous year. Overall sustainability has improved based on the dramatic increase in the SKI score for all urban areas in Kuwait. For example in figure 41, the SKI score for the Abdullah Al-Mubarak area jumps from 53% to 62.5% for the second scenario and to 63.5% for the first scenario.

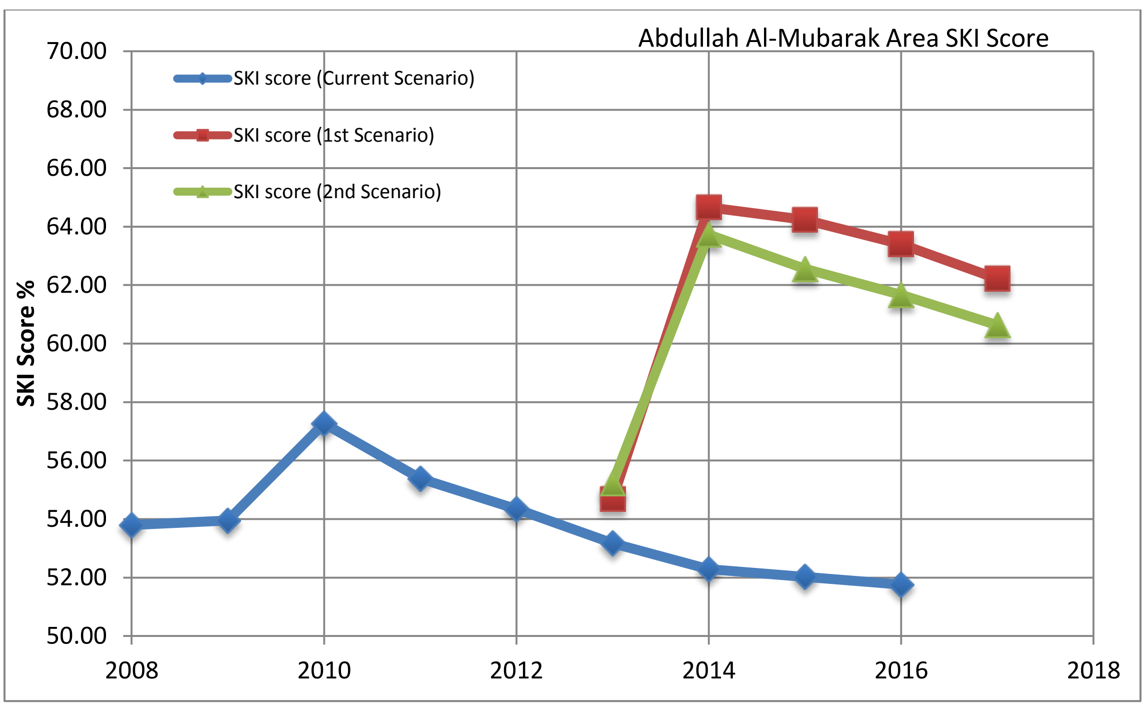


Figure 41 SKI score under 3 scenarios for Abdullah Al-Mubarak area

Table 23 Projection of SKI Indicators scores under 2nd scenario for Abdullah Al-Mubarak in 2014

Category	SKI Indicators	Indicator Score (%)	Score (%)
Resources	**Indicator 1:** Availability (R_{av})	26	33
	Indicator 2: Renewability (R_r)	0	
	Indicator 3: Recharge (R_{ASR})	77.42	
	Indicator 4: Demand (R_D)	30	
Infrastructure	**Indicator 5:** Storage (I_s)	39.5	81
	Indicator 6: Demand (I_d)	94	
	Indicator 7: Safe Water (R_{sws})	100	
	Indicator 8: Network (I_N)	90	
Capacity	**Indicator 9:** Resilience (C_{rs})	N/A	74.2
	Indicator 10: Access (C_a)	100	
	Indicator 11: Reliability (C_r)	100	
	Indicator 12: Consumption (C_{Capita})	22.5	
Socio-economic	**Indicator 13:** Emission CO_2 (S_{CO_2})	87.2	66.5
	Indicator 14: Emission SO_2 (S_{SO_2})	89	
	Indicator 15: Emission NO_2 (S_{NO_2})	66.4	
	Indicator 16: subsidy (S_S)	10.75	
SKI index			**63.67**

SKI indicators analyzed the second proposal scenario for reforming the water price policy. The Abdullah Al-Mubarak area was selected among 78 areas to show the results of SKI indicators due to the second proposal scenario. In the second year (2014) for the second proposal scenario, the resource category received 33%, which is the average of the following indicators:

- Availability indicator: 26% (It was 7% in 2012 based on current water price)
- Renewability indicator: there was no increase in renewability of groundwater per capita during this study.
- Artificial recharge of groundwater: 77.4 %
- Demand indicator: water consumption decreased due to the new water price policy. As a consequence, the demand indicator increase to 30% (It was 23% in 2012)

The water infrastructure category scored 81% in 2014 under the second proposal scenario. The following scores for storage, demand, safety of water, and network were 39.5%, 94%, 100%, and 90%, respectively.

The capacity category represents the vision of policymakers to improve the water sustainability in Kuwait. The score of the capacity category was 72% under the current scenario in 2012 and it has increased to 74.2% under the second proposal scenario. The following points describe the characteristics of 4 indicators in this category:

- The accessibility to water (100%)
- The status of water consumption per capita from 150 L (22.5%)

- The ability of a system to recover if there is drop in water pressure
- The reliability of a water system to provide water without interruption (100 %)

Finally the socio-economic category shows the role of society to sustain the environment and government budget. CO_2, NO_2, SO_2 are the most important pollutants that are emitted from desalination plants in Kuwait. The government subsidy is the difference between the actual water production price and the consumer price. The score of the socioeconomic category increased from 59.5% under the current water price scenario to 66.5% under the free allowance followed by \$1.6 per m^3 scenario. Overall SKI indicators scores under the second proposal scenario have slightly lower values than in the first proposal scenario for the water price policy. This is due to the first scenario providing more reduction in water consumption than the second proposal scenario. The following figures show SKI scores under current, first and second scenarios in 2014. SKI scores obviously were increased under the proposal of water price comparing with current water price in Kuwait. The following figures (42, 43, and 44) are the projection of SKI scores for Abdullah Al-Mubarak under 3 different scenarios in 2014

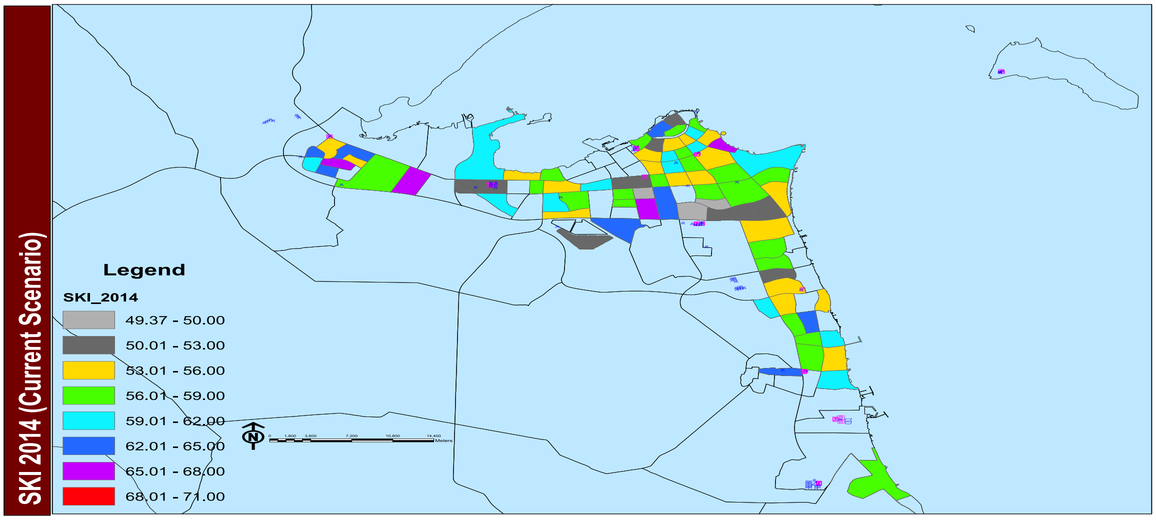


Figure 42 SKI score in 2014 for urban areas in Kuwait under current water price

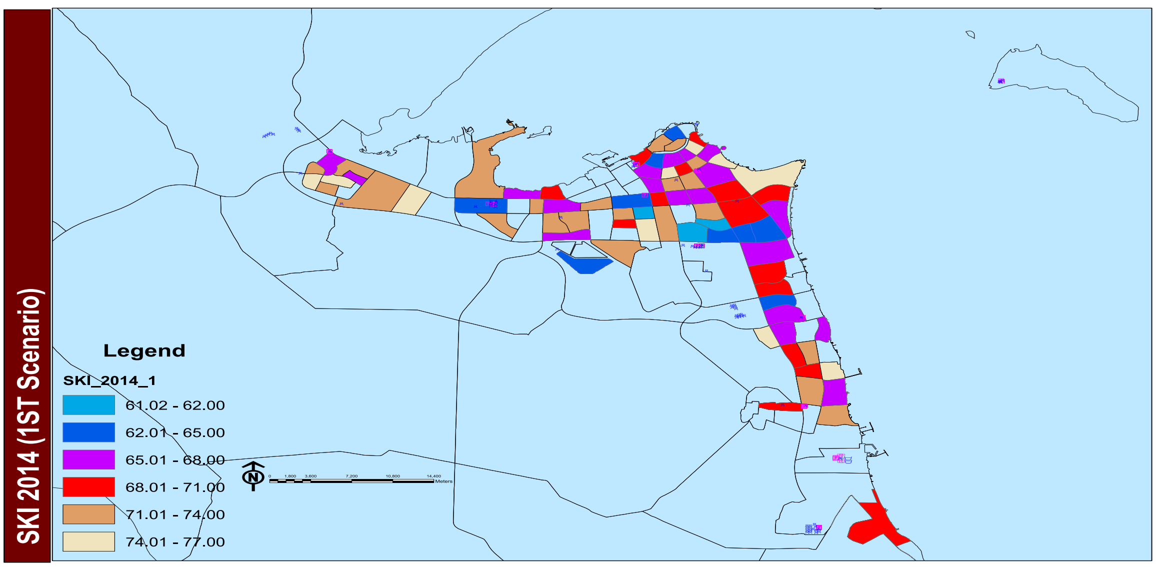


Figure 43 SKI score in 2014 for urban areas in Kuwait under 1st scenario for water price

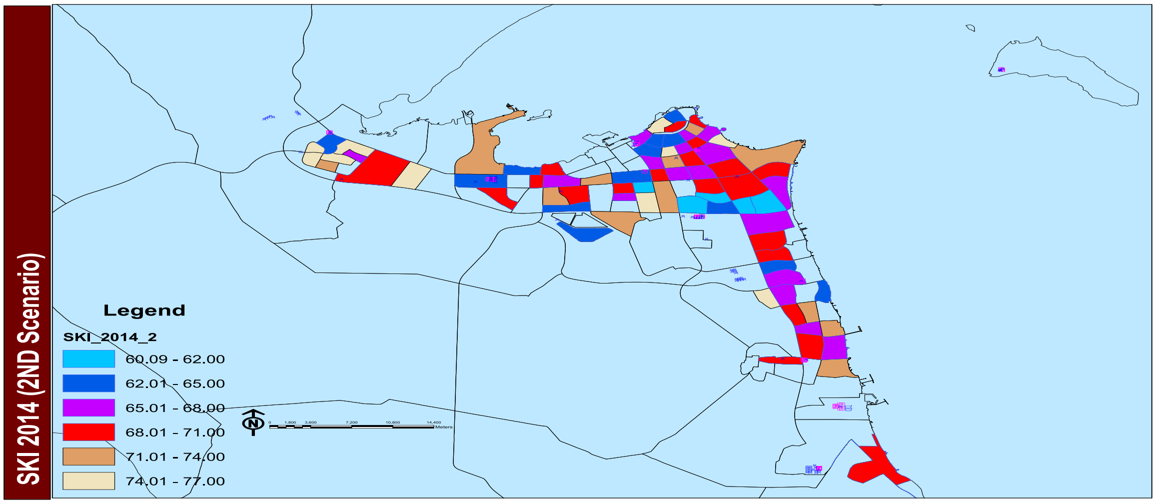


Figure 44 SKI scores in 2014 for urban areas in Kuwait under 2nd scenario for water price

This study brings the following components 1) sustainable water network modeling, 2) analysis tools and sustainable indicators, 3) water price together to integrate water management in Kuwait. Oil products are the main sources of income for the government of Kuwait and with the dramatic increase in water consumption, there would be a decrease in the oil products that are exported to the global market. The reduction in oil products revenues is to meet the requirements of the desalination plants. The second proposal scenario reforms the current water price policy by encouraging the consumers to consume water wisely in order to get this utility for free. This proposal scenario is acceptable for both consumers and policymakers and gains economic and environment benefits for both sides.

Next chapter illustrates the significant points that have been achieved in this research and answers the research questions. Also, this research are applicable and for Kuwait and gulf countries, KSA, Bahrain, Qatar, UAE, and Oman, since there are following the same strategy to reduce wasteful energy and to save oil products.

CHAPTER 6: Conclusion and Future works

In the absence of surface water resources and because groundwater capacity is limited to $60m^3$/year per capita, constructing dual-purpose desalination plants that produce electricity and water was the best option in Kuwait for providing fresh water to the population. Two specific factors have encouraged the Kuwaiti government to adopt desalination plants to secure fresh water. The first is the availability of fossil fuels that can be used to produce fresh water, and the second is accessibility to the sea due to Kuwait's location near the Arabian Gulf. The rapid increase in population and standards of living has led to the necessity for increased production in desalination plants to satisfy water demands. Increasing the productivity of desalinization plants is a supply approach to meeting increases in water demands. A supply approach (increase the capacity of desalination plants) was the best option at the beginning of the oil revolution, but it was not the optimal solution. Currently, the fossil fuels required to operate desalination plants consume 54% of oil production revenues, the main source of the nation's income. There are many methods other than the supply approach to mitigate water overconsumption caused by the rapid increase in population and unaware of water value, such as: (a) reconsidering water pricing policy, (b) reducing water demand through the use of water-conserving devices, and (c) using renewable energy in desalination plants like solar and wind energy. The scarcity of freshwater supplies and the overconsumption of water in Kuwait have both accelerated the need for integrated sustainability planning and management for the country's water systems while taking environmental and socioeconomic factors into consideration.

The following issues were questionable and had not been addressed before beginning this research:

- The sustainability of the water system in Kuwait was unknown
- Low consumer water price in Kuwait have resulted in high per capita water consumption (464L/C/day in 2011).
- There were no water demand models that could predict water usage at different price levels.
- In order to control and monitor the water distribution network in Kuwait, sustainable water modeling is needed.
- As a consequence of high water consumption, supply management was putting pressure on the consumption of oil products in desalination plants to meet demand.

Water supply systems play an important role in achieving the ultimate goal of water sustainability. Sustainable water supply systems must be designed and operated so as to: minimize energy use, maximize efficient use of water as a resource, and limit (or even decrease) the associated environmental impacts of water usage. In Kuwait, dramatic increases in water demand have always been solved by means of supply management (i.e., build a new desalination plant) and this has required money and time. Meanwhile, in Kuwait, demand management such as reforming water pricing policy has not been considered as a tool to reduce wasteful water consumption or even to make consumers aware of the real economic value of water. This research has provided analytical results demonstrating how to reform water pricing along with other tools that increase knowledge on the sustainability of water systems. Achieving this for present and future generations may be possible if adequate modeling tools are available to facilitate decision-making support for the design, planning, and operation of these systems. Consequently, this research provides the following solutions, which work together and in parallel:

1. Model Urban City (MUC)
2. Sustainable Water System and Infrastructure of Kuwait (SWSIK)
3. Sustainable Kuwait Index (SKI)
4. Proposed Water Pricing Policy (2 scenarios)

This research is dependent on three foundations; which are MUC, SWSIK, and SKI. Initially, they characterize sustainability in Kuwait and analyze environmental and economic impacts under the current water price policy during the period of 2008-2012. Based on these results, I conclude that reforming current water pricing policy is essential to increasing the current water system's SKI score, reducing the usage of fossil fuels in desalination plants, and postponing the expansion of the water distribution network. Two water price policy scenarios have been proposed for implementation to replace the current water pricing policy (0.624 per m^3). The first scenario recommends that a constant price of \$1 per m^3 be charged for water. The second scenario involves a different structure for water pricing: a free allowance (150−250 L/C/day) followed by a constant price of \$1.6 per m^3 for more than 150 L of water. The time frame for testing both proposed scenarios is 2013 to 2017. The suitable amount of free allowance was selected by looking at other countries such as Germany, Finland, Belgium, the Netherlands, Denmark, and Spain, who all consume almost 150 L/C/Day. As a result, the second scenario provides 150 L/C/Day as a free allowance, and any water usage over the free allowance costs \$1.6 per m^3.

The Model Urban City (MUC) is an interactive framework inside ArcGIS. A MUC consists of three components: system structure, scenarios, and system boundaries. In the first approach, MUC provides the engineering field in Kuwait with a modeling program that has the ability to simulate and optimize past, current, and future scenarios with regard to the existing water system. Integrating the water distribution system into Arc GIS (MUC) led to the creation of a new analysis tool, the sustainable water system and infrastructure of Kuwait (SWSIK), which can identify problems and characterize weaknesses in the water system and its infrastructure. SWSIK is a comprehensive, analytical tool that defines the vulnerability, reliability, connectivity, and robustness of water distribution systems. In addition, the SWSIK tool relies on varying scenarios regarding water pricing to predict the economic and environmental consequences of implementing that scenario.

The sustainable Kuwait index (SKI) provides a unified code to measure sustainability in terms of environmental and socioeconomic criteria. The purpose of the SKI indicators is to measure the trend of sustainability for each specific area and to let each indicator characterize how close the area is to a sustainable level. The SKI can provide policy-makers with a marker on the effectiveness of applying policies such as:

1. Water pricing reform
2. Expanding water infrastructure, and
3. Using renewable energy for water production.

The benefits of implementing a new water-management policy can be judged to be positive if the SKI score increases. An ideal sustainability level can be achieved by applying effective water management tools that consider improvements to the triple bottom line of sustainability. 16 SKI indicators characterize the sustainability in terms of water system. SKI indicators were applied to 78 urban areas in Kuwait. Primarily, The Abdullah Al-Mubarak area was selected as a case study to demonstrate the effects of current scenarios (\$0.624/m^3) on its SKI score. The SKI index overall score was 57.4 % in 2011 using current water prices, which provided sustainability for the Abdullah Al-Mubarak area. The MUC simulated water demand in 2011 through the Infowater application in Arc GIS. The results obtained from MUC simulations concerned the potential of water sources to provide fresh water, the water levels in elevated tower tanks, and the properties of pipelines, such as pressure, head loss, and water flow.

The SWSIK tool evaluated water pricing and its effect on the economy and the environment. Initially, SWSIK determined the value of the energy that was needed to produce water for consumption and the volume of fossil fuels that were used in desalination processing plants based on the current water price in Kuwait (\$ 0.624/m^3).

After implementing the SWSIK tool to analyze environmental and economic aspects for 10 zones that were classified based on elevation, it became evident that there is a high percentage of pollutant emissions resulting from water overconsumption. In addition, government subsidies that decreased prices did not control water consumption due to negligible water pricing for consumers.

Different types of techniques to reduce the dramatic increase in water consumption have been used in Kuwait; however, changing the water pricing structure has not been considered. Accordingly, this research has proposed two scenarios for water pricing policy that would solve the issues related to unsustainable water consumption and its related impacts. Two previous models (those of Tunis and the Kingdom of Saudi Arabia) were adopted and adjusted to comply with the water system in Kuwait in order to estimate water usage at a different water price levels and structures. Water demand models for Tunis (TU) and Saudi Arabia (SA) depend on household income, family size, and the price of water. Eighty-one groups were used in the water demand models, which combined eight classes of family size and five household income groups. The SA model that was adjusted to be applicable in Kuwait has two approaches. The first approach of the SA model determines water demand at different water prices in the absence of a non-water pricing policy. The second approach, the SA 2 model, provides more reduction in water consumption and includes a non-water price policy that informs consumers of the benefits of water consumption conservation and of using efficient devices. In the TU model, consumers were classified into upper and lower income blocks. Each block had specific coefficients for variables in the water demand model. The lower three household income groups represented the lower block, and the higher two household income groups represented the higher block. The three water demand models (SA, SA2, and TU) were simulated in two scenarios: 1) constant price and 2) free allowance with constant price. The SA and TU water demand models provided almost the same water usage at a water price between \$0.6 and 2.6 per m^3. As a result, the author selected \$1.0 per m^3 as the sustainable water price for the first scenario. For the second scenario, the water price was set as follows: a free allowance of 150 L/C/day followed by \$1.6 per m^3 for water consumed over the free allowance limit.

The two scenarios were evaluated along with current water pricing with the aim of proposing a new water-pricing schedule in Kuwait. When it was assumed that the Kuwaiti government will not change the current water pricing structure and that population growth rate remains the same, then it was determined that the capacity of desalination plants cannot meet water demand and that a shortage will occur in 2014 due to a deficit in the supply of water when demand remains the same. In particular, the current price of water (\$0.624 per m^3) provides zero economic value to consumers. The priority for the Kuwaiti government in implementing any new policies or laws is acceptance by citizens and non-citizens for that action. In spite of the results of the first scenario, the government plans to postpone increasing the capacity of desalination plants until 2124. But this might be not acceptable to consumers due to the stigma associated with the resulting increases in prices. The second scenario is more acceptable to consumers and policy makers because it provides vital necessities to the population at no cost and any over usage will be priced. In addition, the second scenario will postpone the need for new desalination plants until 2023 and help consumers to control their consumption. Water pricing in the second scenario satisfies the conditions that were established in the limitations section of this research. It provides the minimum requirement of water volume (150 L/c/day) at a highly subsidized price, free of charge, and any usage over the limit is charged for \$ 1.6 per m^3, which is less than equilibrium price. The SWSIK tool analyzed numerous scenarios and water prices and then evaluated the environmental and socioeconomic benefits for each water-pricing scenario. Table 24 illustrates the SWSIK results for this research. It provided an analysis of three different water price scenarios (current water pricing, first scenario, and second scenario) between 2013 and 2017 to illustrate the economic and environmental impacts.

Table 24 The economic and environmental impacts for water price policy scenarios

2013-2017	Water demand (Mm3/yr.)	Demand (Mm3/5 Yr.)	Oil Products (M bbl.)	NG (M SCF)	Total Cost ($M)	Co_2 (M. MT)	No_2 (Th. MT)	So_2 (Th. MT)
Current scenario	670.77	3627.77	80.38	295107	20423	57.45	407.64	757.17
	696.70							
	724.18							
	752.73							
	782.39							
1st scenario	670.77	2713.04	60.13	220758	15277.6	42.98	304.94	566.41
	479.92							
	499.81							
	520.50							
	542.04							
2nd scenario	670.25	2866.31	63.52	233229	16140.7	45.40	322.16	598.41
	520.28							
	541.59							
	557.34							
	576.85							

The time frame to test both water price scenarios is 2013 to 2017. It was assumed that both proposal scenarios would be effective after one year of implementation and the over the last three years of the proposal time frame, water consumption per capita would increase by +2 L/C/day over the preceding year..

Water consumption in first scenario will drop to 321 L/C/day in 2014 in the SA model. In the second scenario, water consumption is 347 L/C/day in the second year. After SWSIK analyzed both water pricing scenarios, it was determined that in the first scenario, the Kuwaiti government could reduce water consumption while saving almost 5 million barrels per year in oil products (crude oil, gas oil, and HFO) and also reducing natural gas usage by 31%. The second scenario could reduce the usage of oil products and natural gas in desalination plants by 26% compared to the current scenario during the proposal period. Therefore, the GDP per capita in Kuwait could increase due to the reduction in fossil fuel usage in desalination plants. The fuel consumed in desalination plants to generate water as a percentage of total fuels consumed in all sectors is equivalent to 12% (Darwish et al., 2008). By applying either the first or the second scenario, fossil fuels consumed in desalination plants as a percentage of total fuels consumed in all sectors would drop to 8.8%.

The SWSIK tool determined that the following pollutants would result from burning fossil fuels in desalination plants. CO_2, SO_2, and NO_2 emissions were computed under the first and second scenarios and compared to the results for the current scenario during the proposal period of 2013 to 2017. The first scenario reduces CO_2 emissions by up to 3.5 million metric tons per year compared to the CO_2 emissions under the current scenario. The reduction in CO_2 emissions under second scenario is 2.4 million metric tons per year. The percentages of the mass reductions in NO_2 and SO_2 emissions are 25 % and 21 % under the first and second scenarios, respectively.

Table 25 Price elasticities from previous studies of water demand

Case Study	Water Price Elasticity	Pricing Structure	Water Consumption (L/C/day)	Source
Australia	-0.63 to -0.77	Free allowance followed by fixed price	143	Dandi et al. (1997)
Denmark	-0.52	Block Pricing	131	Hansen (1996)
Finland	-0.41	Constant Pricing	150	Laukkanen (1981)
Netherlands	-0.3	Constant Pricing	127.5	Environment Agency (2008)
USA	-0.35 to -0.76	Average Pricing	333	Foster and Beattie (1981)
Canada	-0.25	Block Pricing	329	Environment Canada (2013)
South Africa	-0.69	Free allowance followed by fixed price	240	Döckel J.A (1973)
England	-0.15	Block Pricing	150	Environment Agency (2008)
Germany	-0.23	Average Price	139	Schleich and Hillenbrand (2007)
Belgium	-0.2	Block Pricing	110	Environment Agency (2008)
Spain	-0.1	Constant Pricing	280	Environment Agency (2008)
Saudi Arabia	-0.78	Constant Pricing	350	Riazaiza (1991)
Tunisia	-0.17 to -0.41	Average Pricing	486	Ayadi, X. et al. (2003)
France	-0.22	Average Pricing	164	Nauges and Thomas (2000)
Denton, Texas	-0.86	Average Price	-	Nieswiadomy and Molina (1989)
UAE (Abu Dhabi)	-0.1	Constant Pricing	636	Abu Qdais and Al Nassay (2001)

The elasticities of the water demand models were calculated when unit water prices change. An analysis was conducted for price elasticity of demand for water as a consequence of proposal of water price scenarios under 2 water demand models. The elasticities for first scenario of the SA model and the TU model were −0.78 and −.0.75, respectively, while the elasticities for second scenario of the SA model and the TU model were almost the same: −0.763 and −0.759, respectively. Table 25 shows price elasticities for different countries based on previous studies to compare with price elasticity of this study. The demand response in the second scenario has to be re-evaluated by testing it in the real field because the water pricing input used was as an average price. Although water demand is inelastic, water demand models have indicated that water demand is sensitive to the water pricing scenarios that were provided in this study.

Both proposal water price scenarios have a tremendous saving in total cost in proposed period (2013-2017). First scenario is going to save \$5 billion to government budget, while 2nd scenario is going to save \$ 4 billion. Figure 45 shows the percentages of daily water usage for different services in home. The saving due to the proposed water price scenarios can be invested to use more efficient devices to reduce the water flow and install a prepaid water meter to facilitate the payment process. Showers and toilet flushing represent 65 % of daily usage. So the efficient devices can be more beneficial to reduce water consumption in Kuwait by using ultra-low-volume (ULV) toilet and low flow showerhead. As consequences the saving in total cost by implement a new water price policy can be invested in install efficient devices to increase the saving. The previous results lead to if each household saves a little, that can add up to major savings in water, energy and money.

Overall, both proposed water pricing scenarios will increase the SKI score for entire urban areas in Kuwait, postpone for 10 years the necessity of building a new desalination plant to meet the demand, and reduce environmental damage. But the second scenario will be more suitable for policy-makers and consumers because it provides the vital water requirement for free.

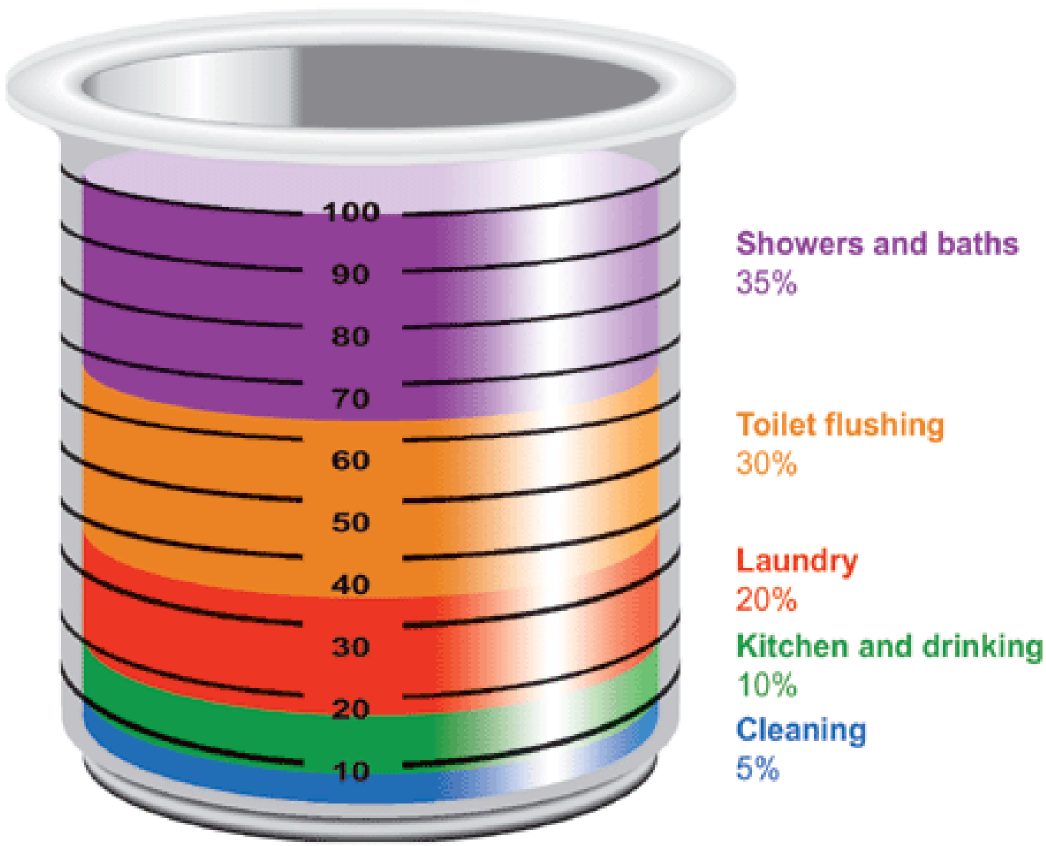


Figure 45 The distribution of services of water usage in home

This research was necessary in order to propose the sustainable water price solution and to increase the advancement of knowledge in the field. MUC, SKI, and SWSIK solutions were the basis of this research in determining sustainability values and reducing water overconsumption by evaluating the effect of current water pricing on economics and the environment.

The objective of this research was to provide three solutions for integrated sustainable management and planning. The aim of sustainable modeling, indexing, and the analysis tools is to reduce water overconsumption and to conserve the nation's main source of income This study suggests that focusing on a water demand management framework to resolve issue related to high per capita water consumption could save fossil fuels, reduce environmental impacts, and postpone the construction of new desalination plants. The SKI index defined the sustainability level during the period of 2008−2012. Current water price projections (2013−2017) are drifting away from sustainable water systems. The following points are signals of the projected path of current water pricing:

- A decrease in the SKI index (from 59 % in 2008 to 56 % in 2017)
- An increase in the annual demand on oil products to 17 million barrels.
- By the end of 2014, water demand will exceed production capacity of the current desalination plants, which the shortage will occur.

However, both of the proposed water pricing scenarios will increase the sustainability of the water system by reducing waste in water consumption. If one of them is adopted to replace the current water pricing system, they will provide 25−30 % reductions in water demand. As consequences, the demand on oil products will decrease to 12 Million barrels from 1st scenario and 13 Million barrels from 2nd scenario. Based on current water price in year 2012, the demand on oil product was 14 Million barrels. In addition the reduction in natural gas from 1st and 2nd scenarios are 31% and 26%, respectively. As a result, applying a reasonable water pricing structure such as the second scenario can reduce water consumption in Kuwait and also succeed in diminishing wasteful water consumption. Immediate actions to reform water pricing will be reduced losses in future.

This research contributes to providing analytical approaches to reforming water pricing policy by adopting water demand models from previous studies that correlated with the case study. The added value of this research is that it provides a sustainable water price of a 150 L/c/day free allowance followed by $1.6 per m^3 as an acceptable price between the subsidized price and the equilibrium price. Sustainable water price balances the water-energy relationship. This water price structure provides real economic value and provides the water that is necessary for consumers for free. In addition, the significant of this research was proposed a new strategy in government subsidy by providing free allowance of water. This study provide the following components that lead to defines the sustainability in region that has no surface water resources and depends entirely on oil products to secure the water and economy:

1. Sustainable water network modeling
2. Analysis tools and sustainable indicators
3. Sustainable water price

The author is considering for future research proposing a block tariff structure scenario for water pricing schedule and comparing it with the other scenarios that have been implemented in this research. In addition, it will illustrate the important role of solar energy in generating water in desalination plants, especially if the Kuwaiti government initiates the proposed solar energy station to the northwest of Kuwait City to supply desalination plants with the energy that they require. The relation between temperature and water consumption should be considered as an essential factor in analyzing water systems in Kuwait. A further suggestion is that the demand response in second scenario, the free allowance followed by the constant price, should be tested with real data from the field. Because this research has used the average price of two parameters to form the price, the price has to be tested with real consumption behaviors. Overall, the results of this research can be applicable in Kuwait if consideration is given to the possibilities that the demand response might be different, incomes may or may not be the same as in the model, and the annual increase in the population may vary from the estimate of 3.5%.

CHAPTER 7: Appendix A:

Table 26 the properties of Fossil Fuels (Citation: www.KPC.com)

Fossil Fuels	% wt. Sulfur	% wt. Nitrogen	% wt. Carbon residue	Density (bbl/M.T)
Crude Oil	2.645	0.15	10	7.192
Heavy Fuel Oil	3.5	0.5	11.3	6.49
Gas Oil	0.206	0.174	0.36	7.458

$S + O_2 \rightarrow SO_2$

$N_2 + O_2 \rightarrow 2NO_2$

$C + O_2 \rightarrow CO_2$

Table 27 the properties of Natural Gas (Low Pressure) (Citation: www.KPC.com)

Component	Value
Hydrogen Sulphide (H_2S)	0.03 %
Nitrogen (N_2)	1.42 %
Methane (CH_3)	80.75 %
Ethane (C_2H_6)	13.4 %
Propane (C_2H_8)	4.4 %
Density (SCF/M.T)	41086.737

$N_2 + O_2 \rightarrow 2NO_2 + H_2O$

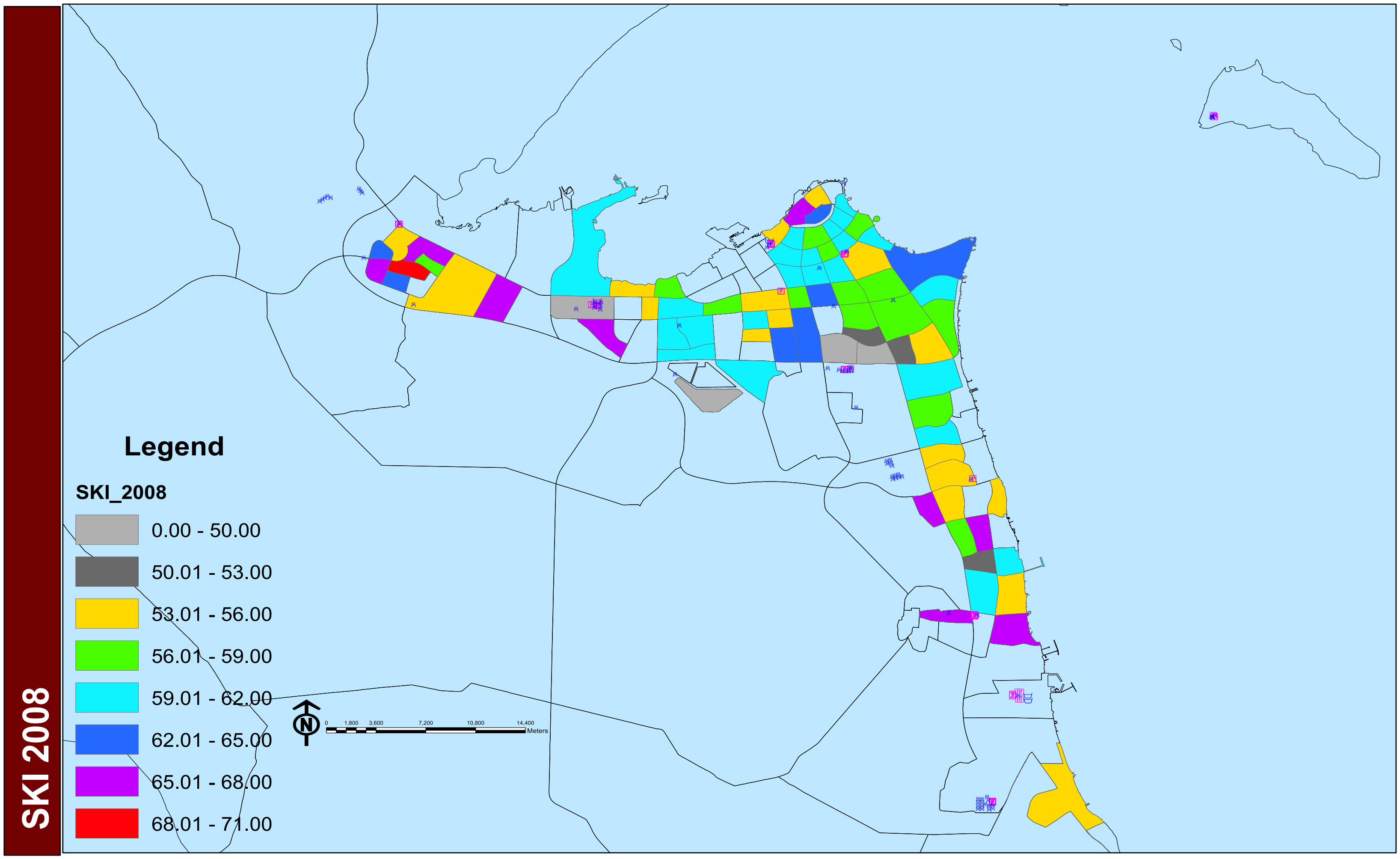
$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$

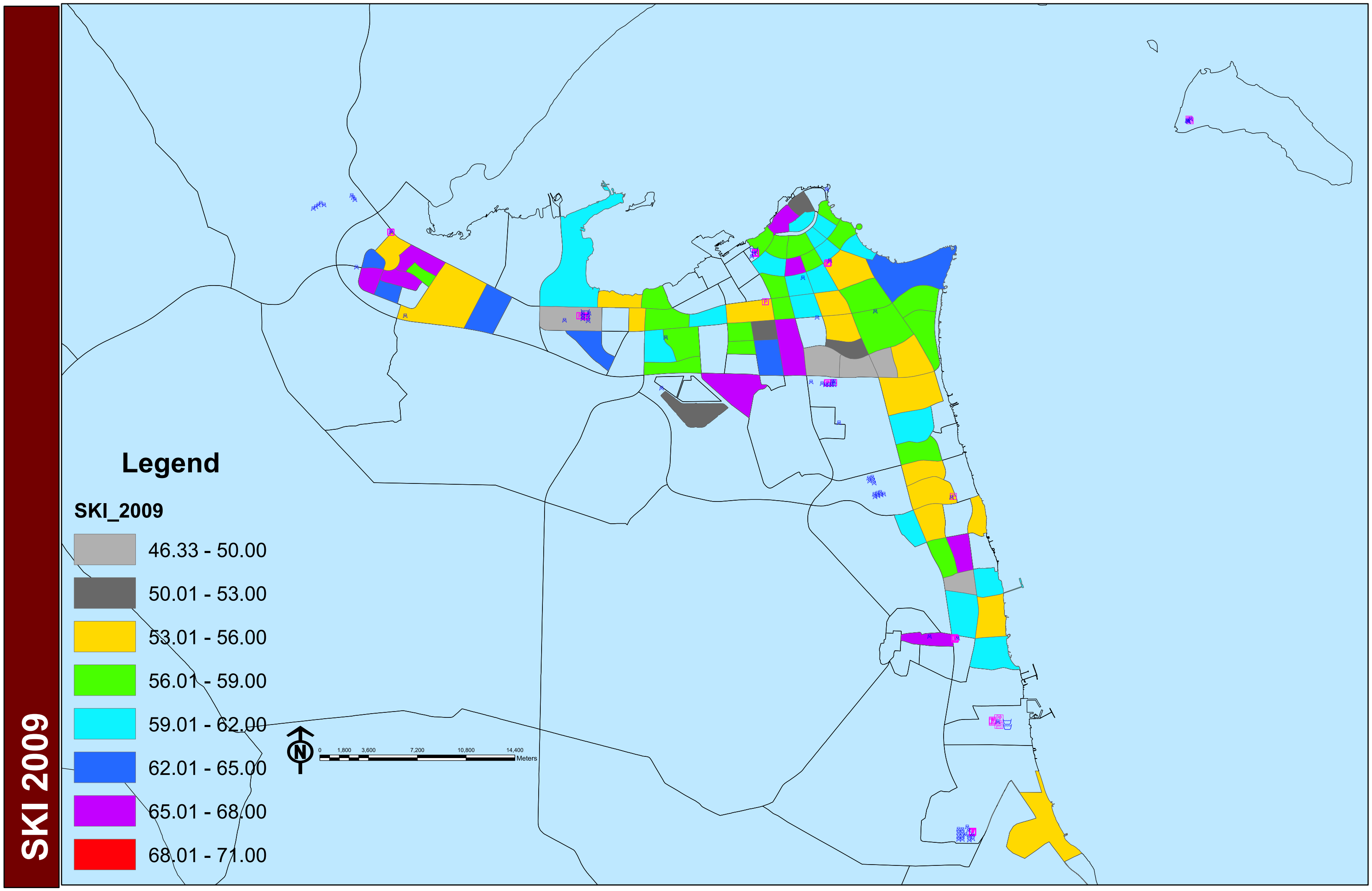
$$\left.\begin{array}{l} CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \\ 2C_2H_6 + 7O_2 \rightarrow 4\,CO_2 + 6\,H_2O \\ C_3H_8 + 5O_2 \rightarrow 3\,CO_2 + 4H_2O \end{array}\right\} \text{Generate } CO_2$$

CHAPTER 8: Appendix B:

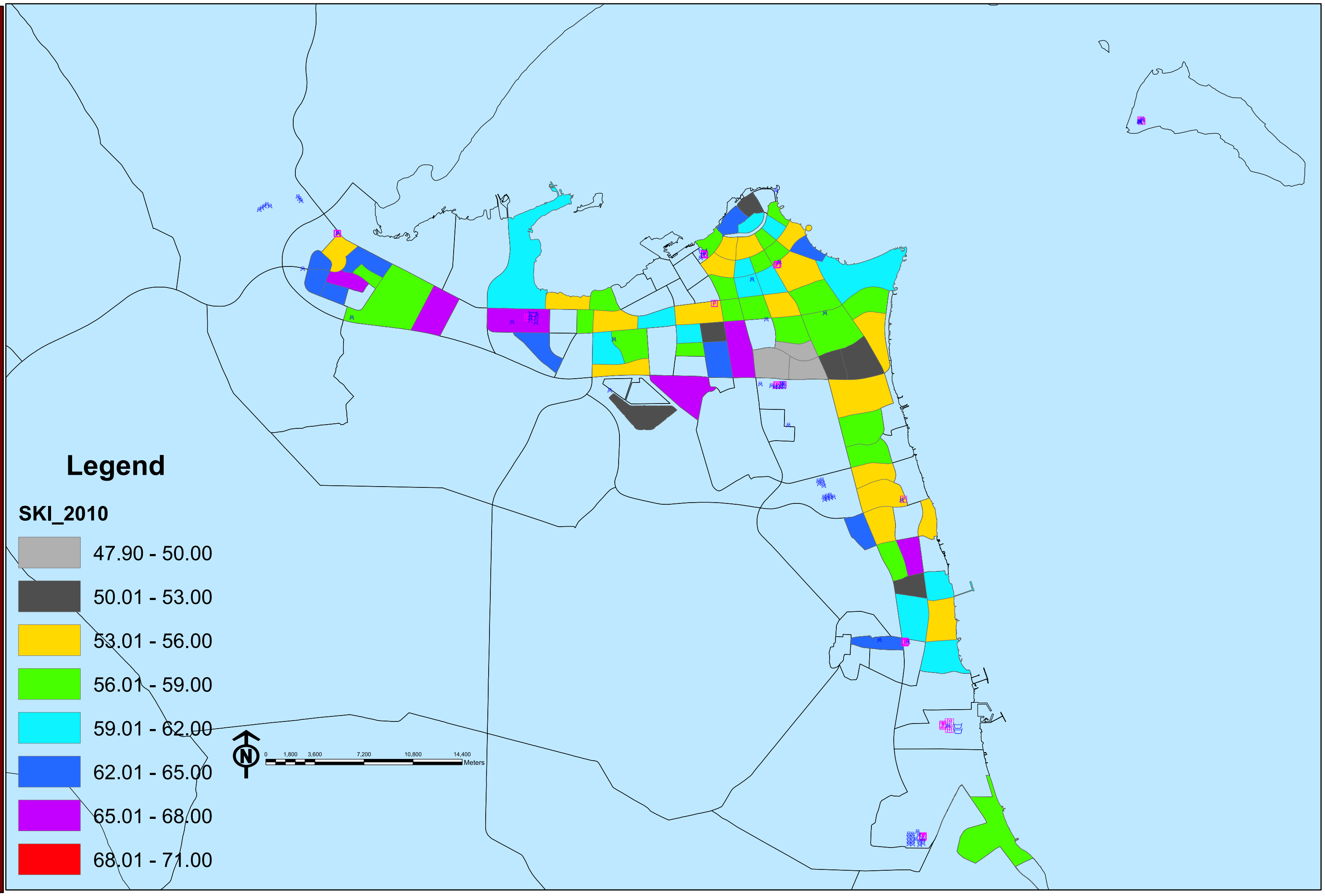
SKI results for urban areas in Kuwait between 2008 and 2017 under 3 scenarios for water price

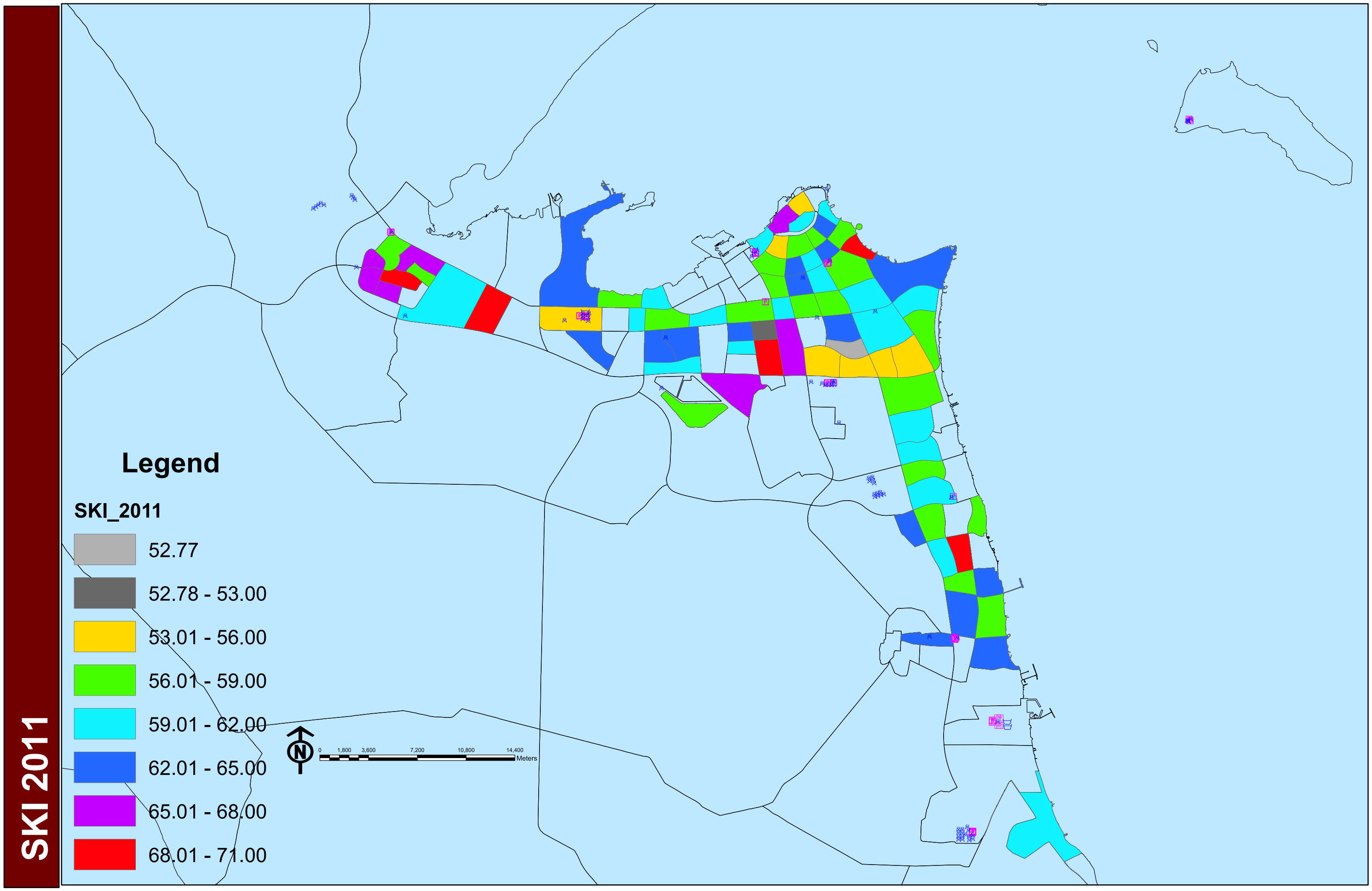
8.1. Current water price (2008-2012)

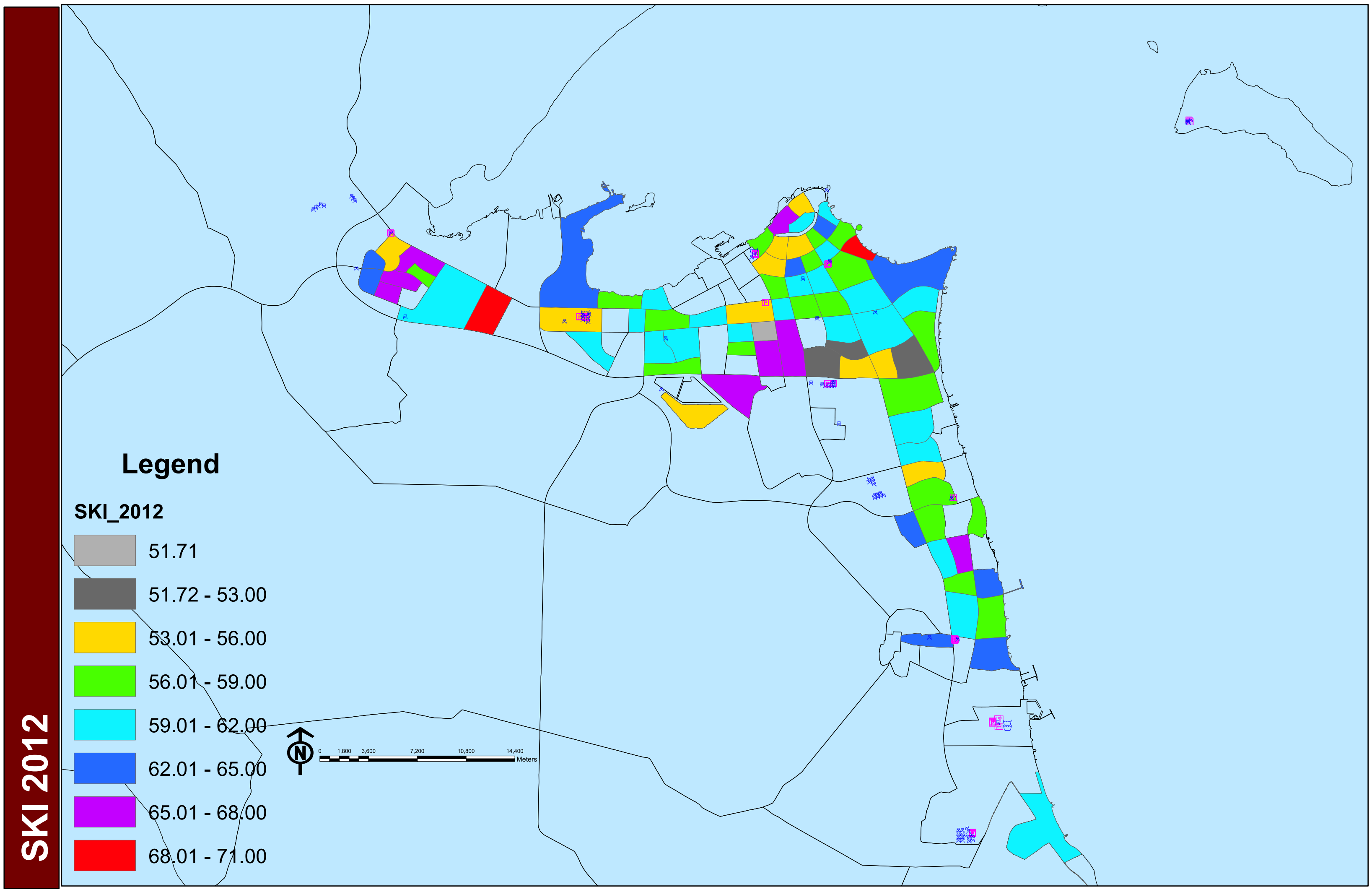



SKI 2009
Legend
SKI_2009
46.33 - 50.00
50.01 - 53.00
53.01 - 56.00
56.01 - 59.00
59.01 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
N
0 1,800 3,600 7,200 10,800 14,400
Meters

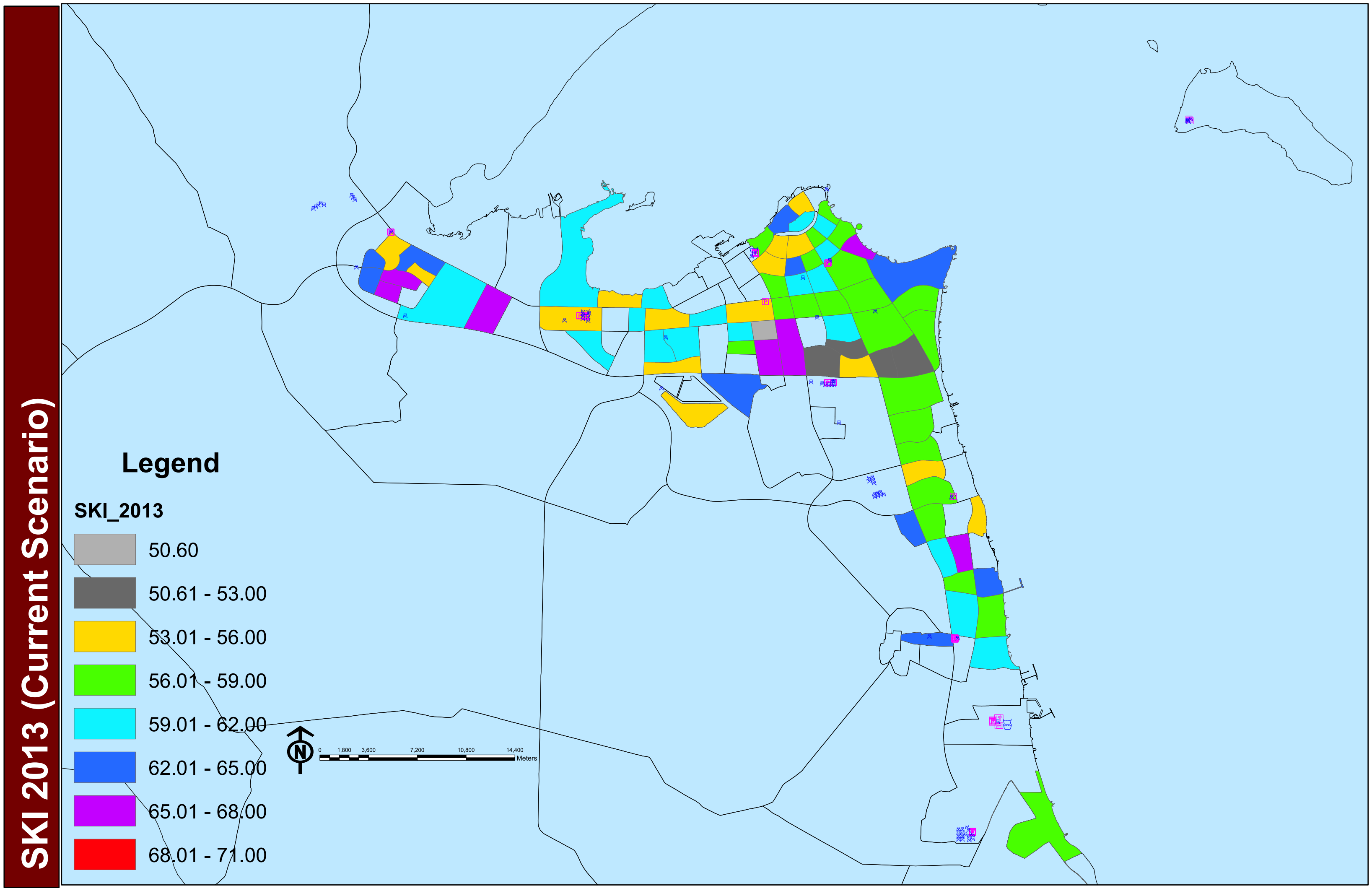
SKI 2010


Legend
SKI_2010
47.90 - 50.00
50.01 - 53.00
53.01 - 56.00
56.01 - 59.00
59.01 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
N
0 1,800 3,600 7,200 10,800 14,400
Meters

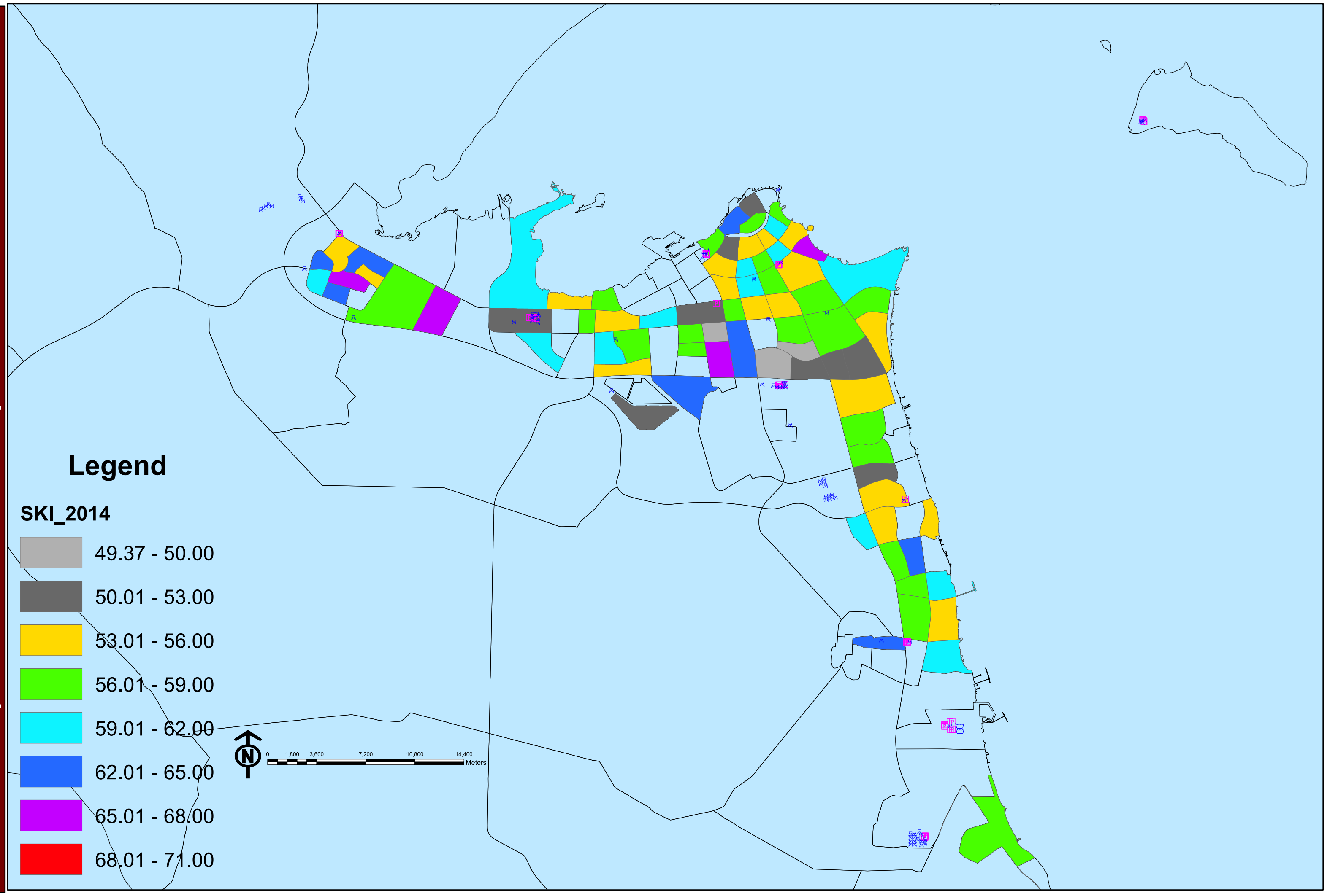

SKI 2011
Legend
SKI_2011
52.77
52.78 - 53.00
53.01 - 56.00
56.01 - 59.00
59.01 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
N
0
1,800
3,600
7,200
10,800
14,400
Meters


SKI 2012
Legend
SKI_2012
51.71
51.72 - 53.00
53.01 - 56.00
56.01 - 59.00
59.01 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
N
0
1,800
3,600
7,200
10,800
14,400
Meters

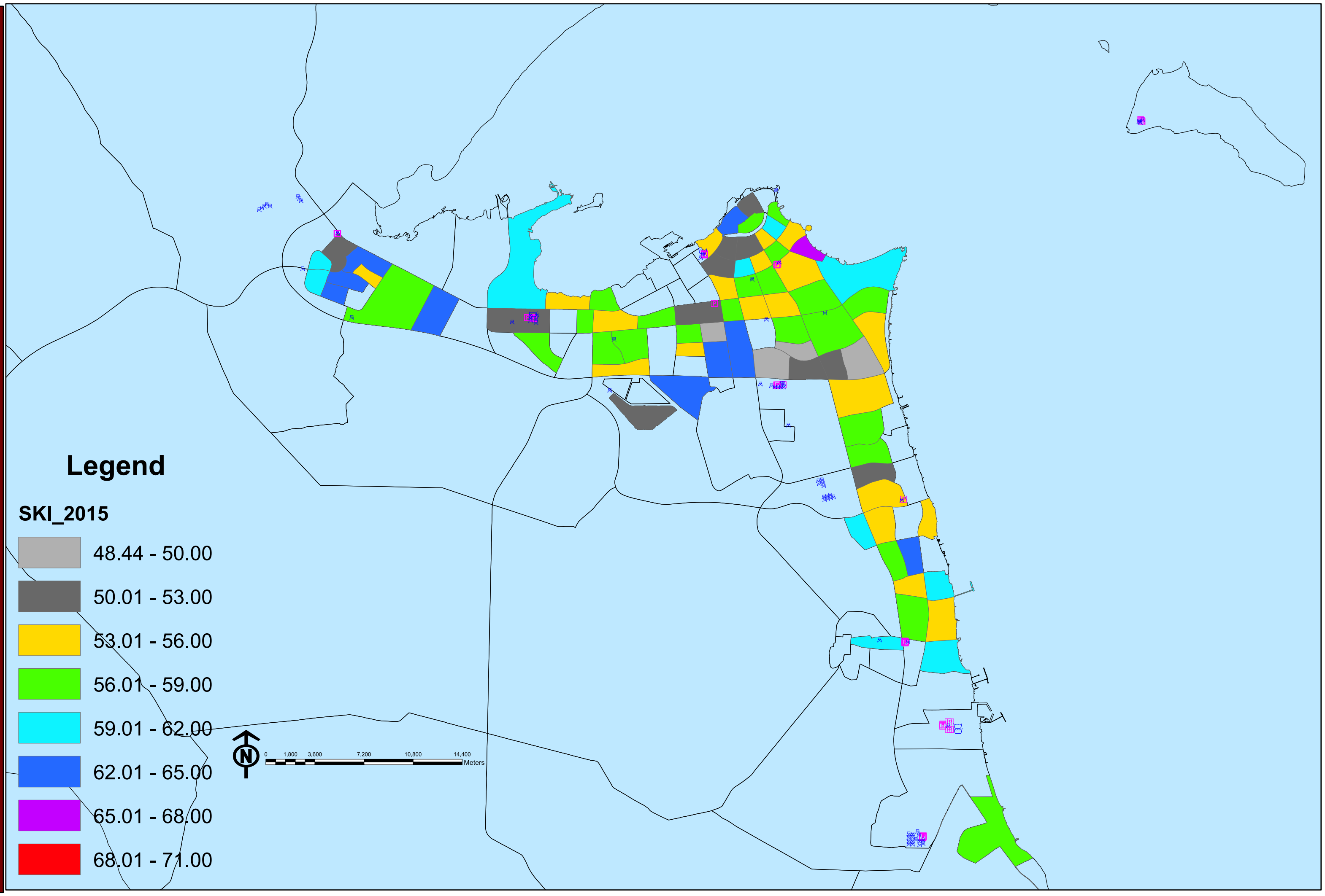
8.2. Current scenario (2013-2017):



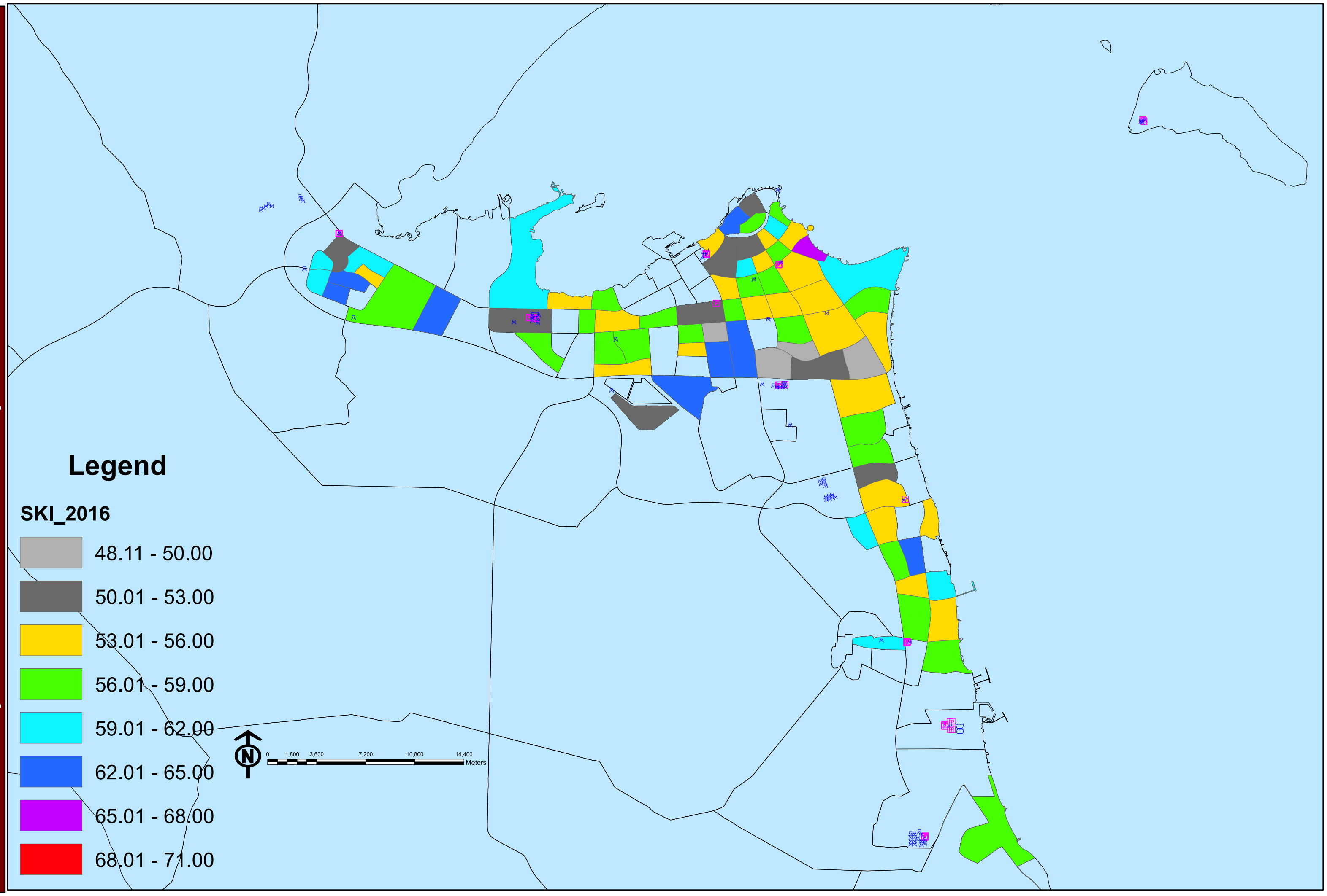
SKI 2014 (Current Scenario)



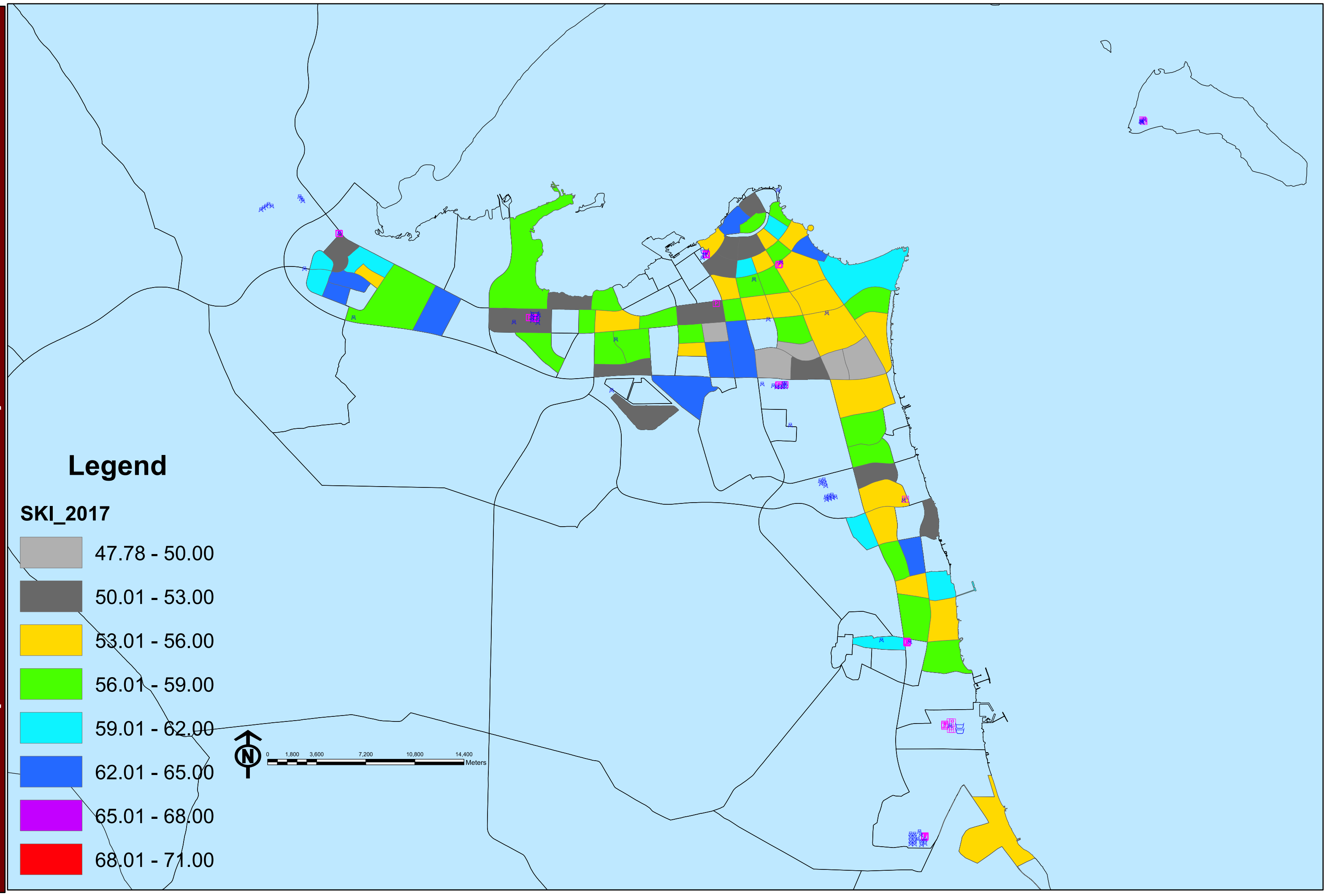
SKI 2015 (Current Scenario)



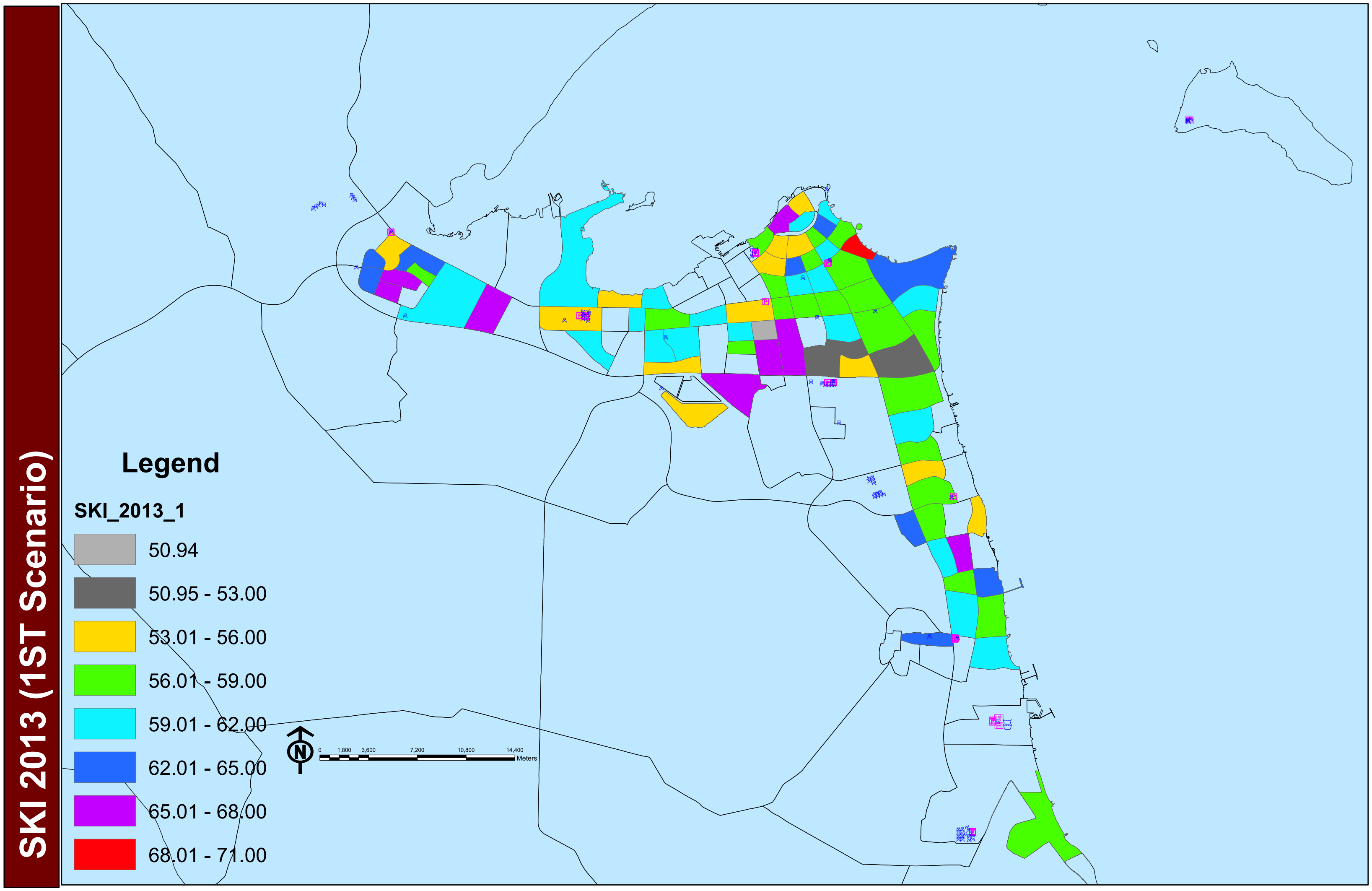
SKI 2016 (Current Scenario)

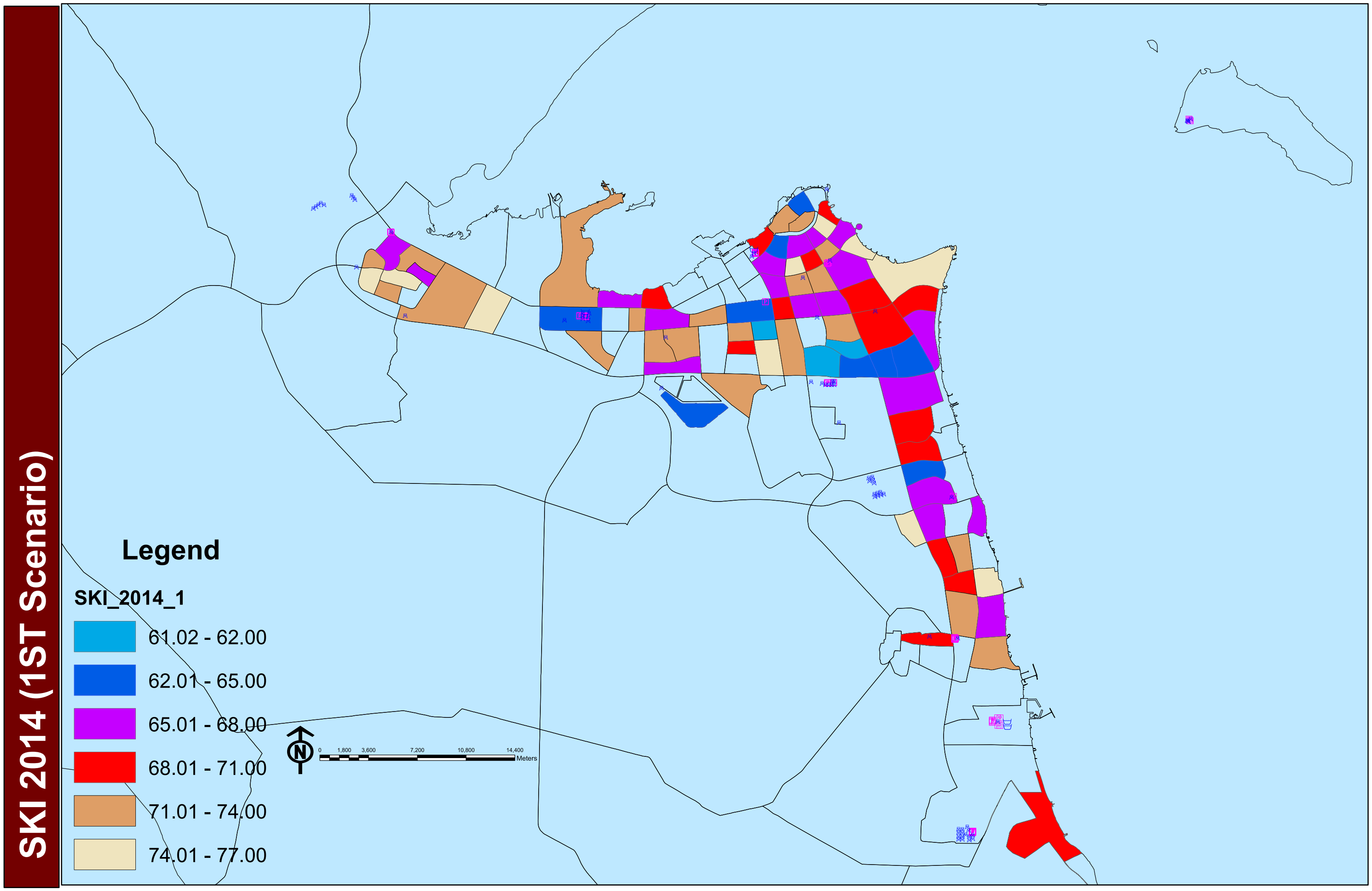


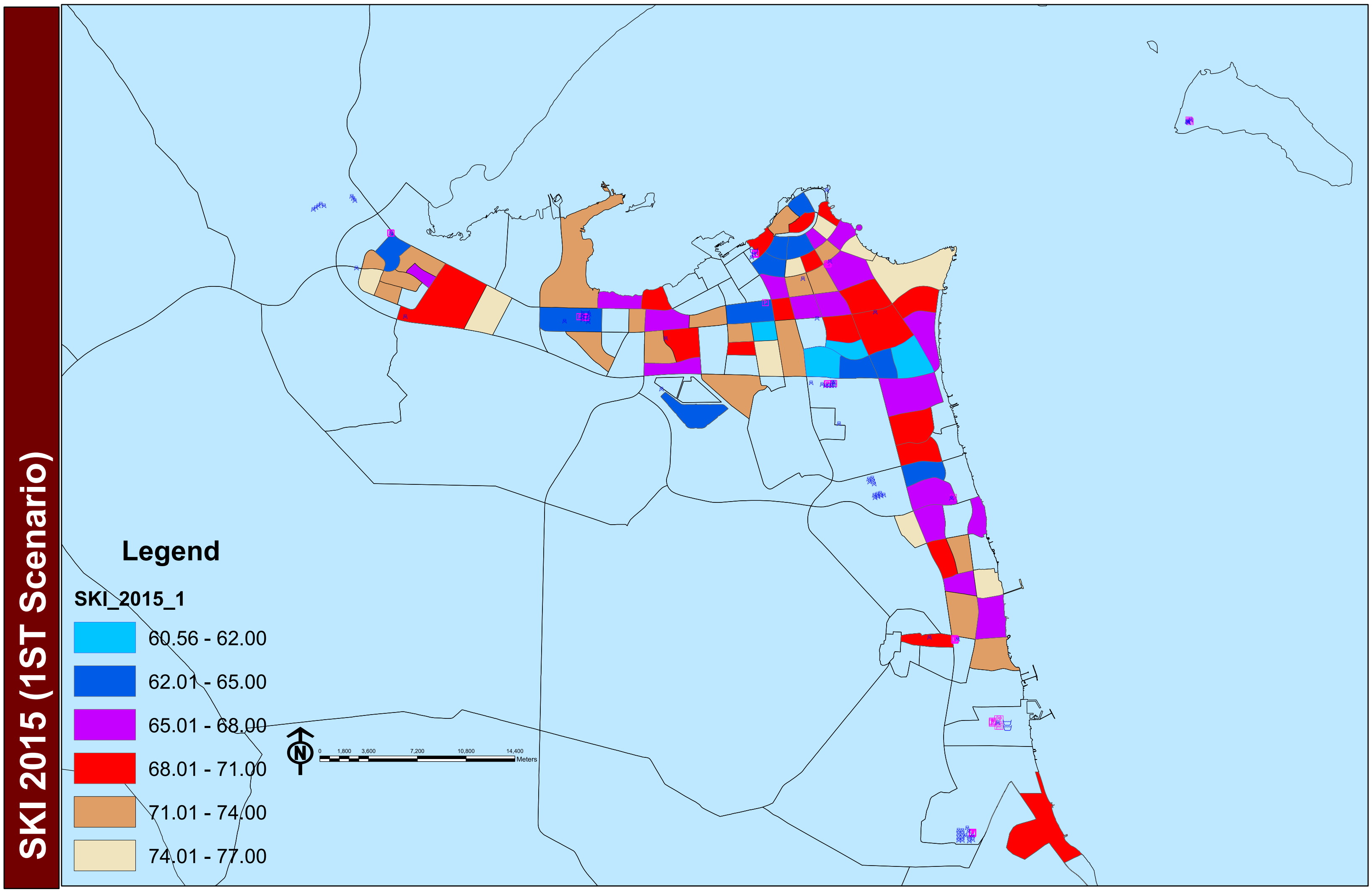
SKI 2017 (Current Scenario)

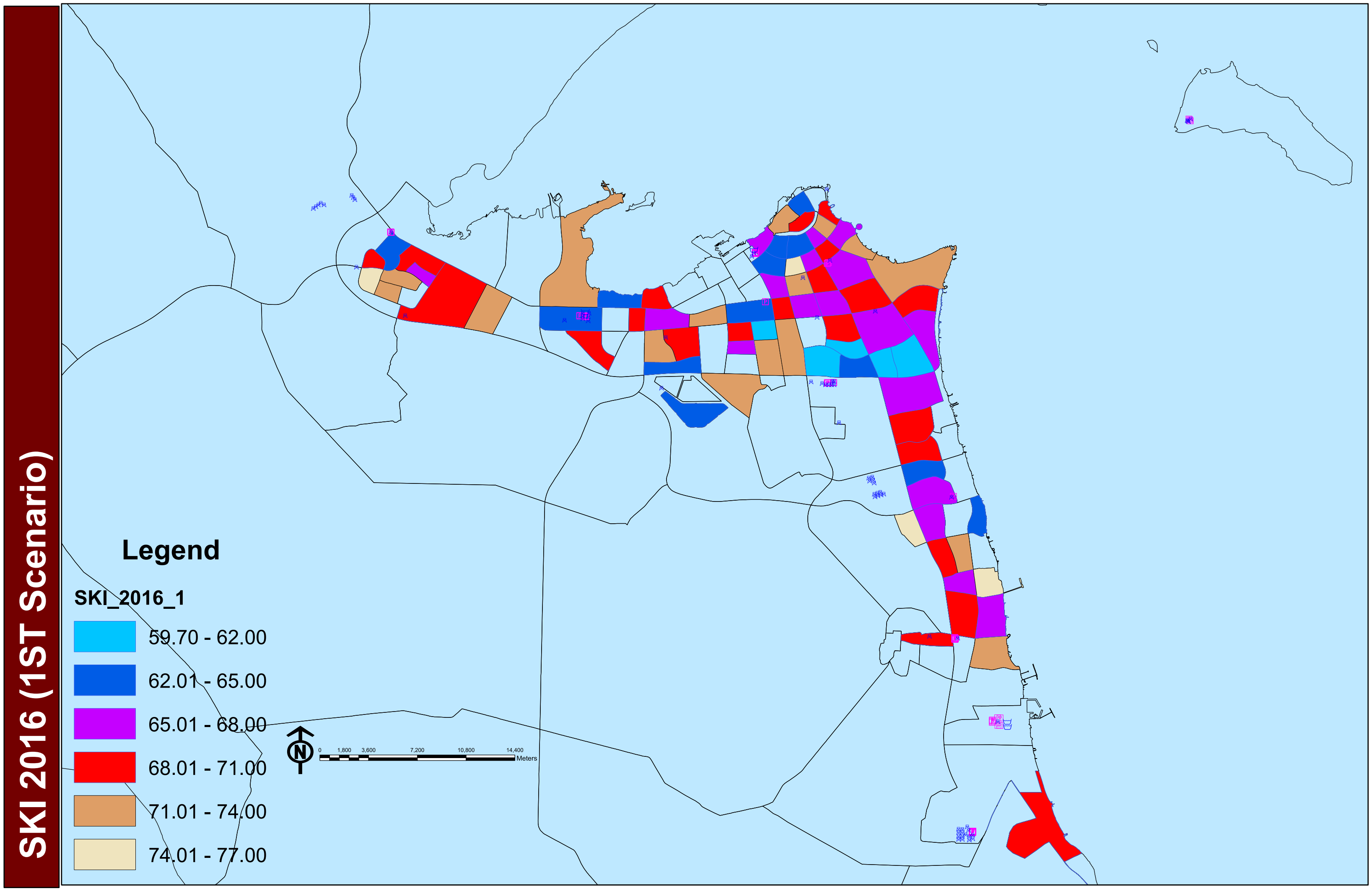


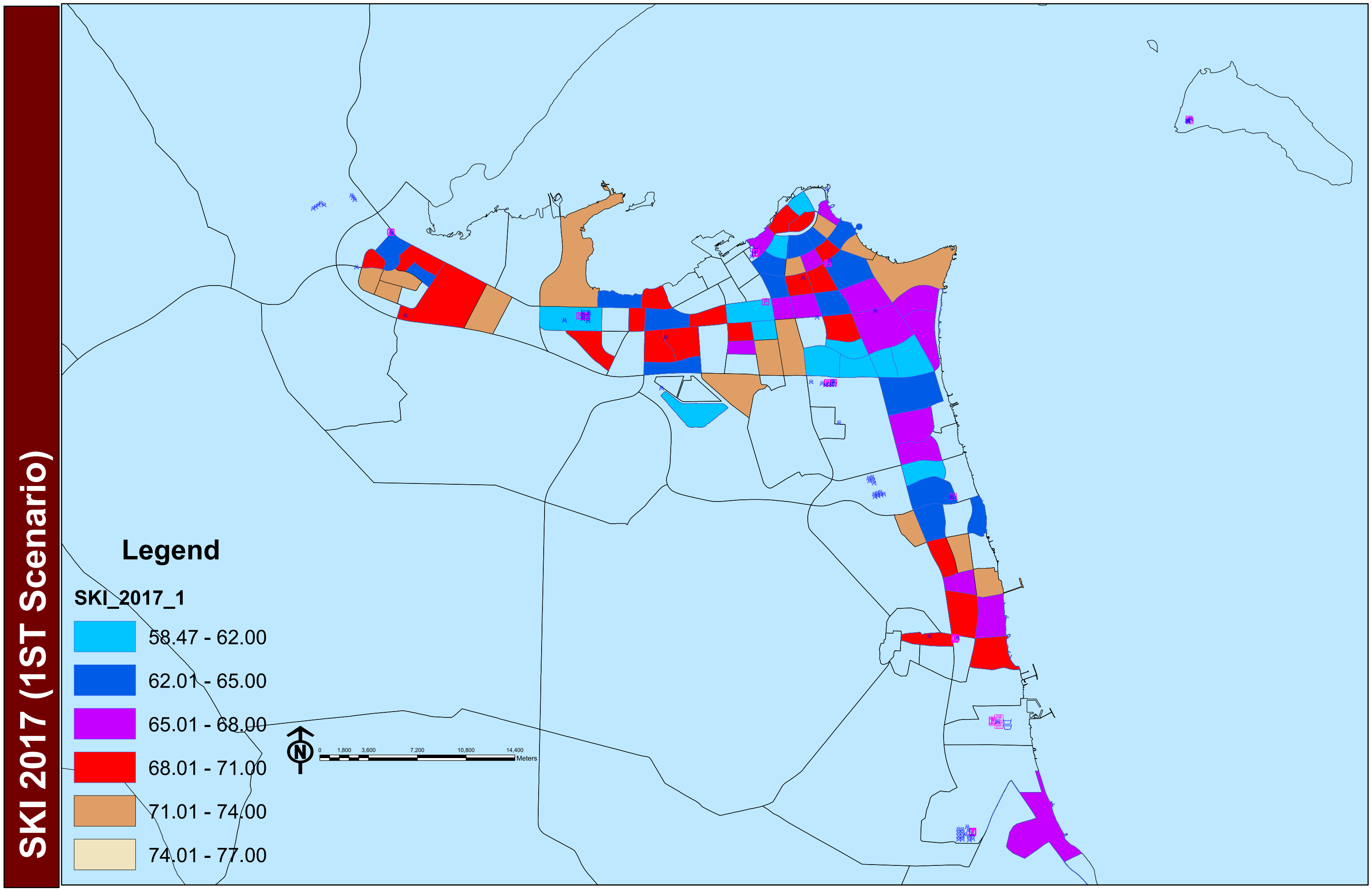
8.3. 1st Scenario (2013-2017):




SKI 2014 (1ST Scenario)
Legend
SKI_2014_1
61.02 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
71.01 - 74.00
74.01 - 77.00
N
0
1,800
3,600
7,200
10,800
14,400
Meters

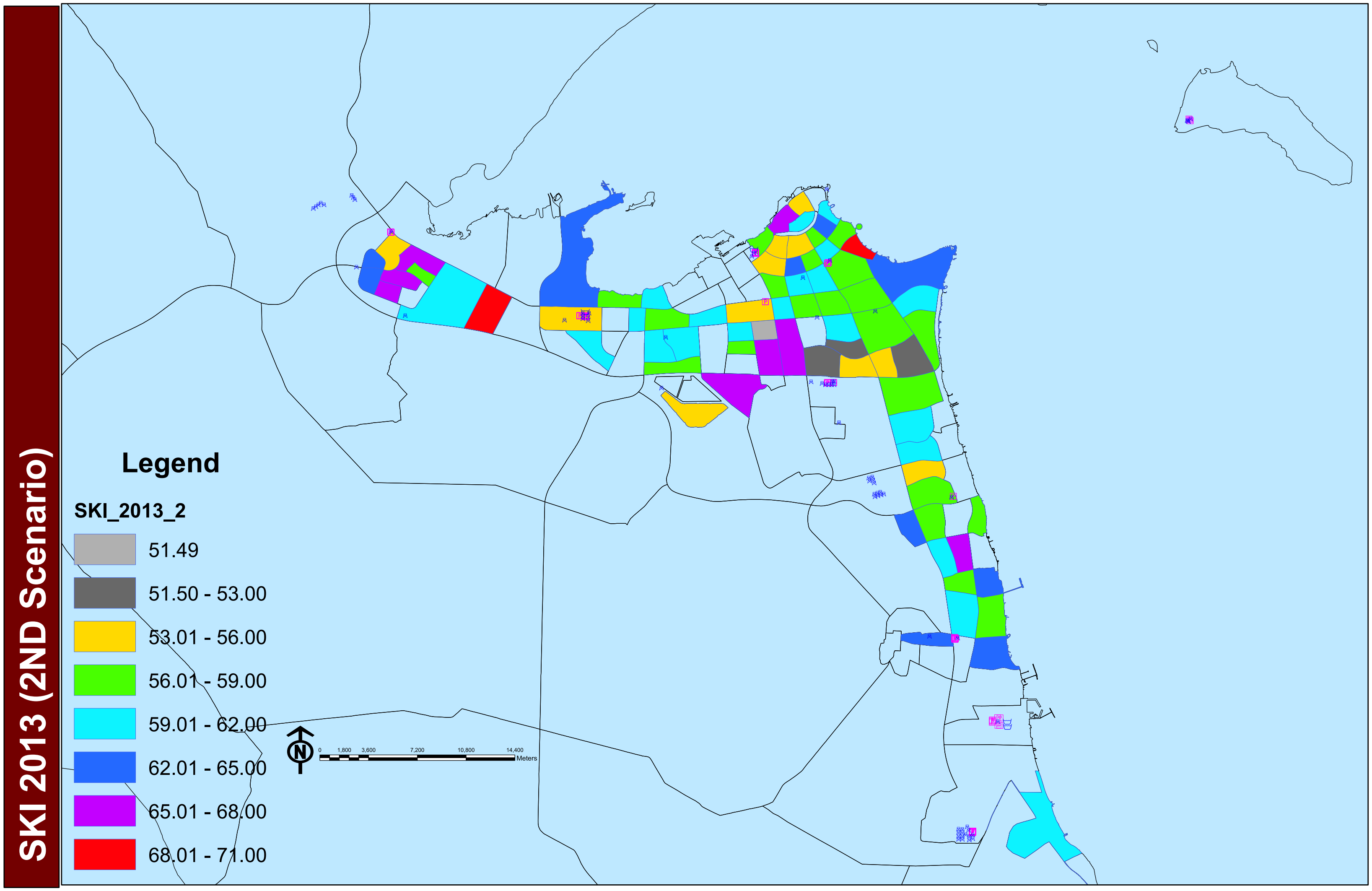

SKI 2015 (1ST Scenario)
Legend
SKI_2015_1
60.56 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
71.01 - 74.00
74.01 - 77.00
N
0
1,800
3,600
7,200
10,800
14,400
Meters

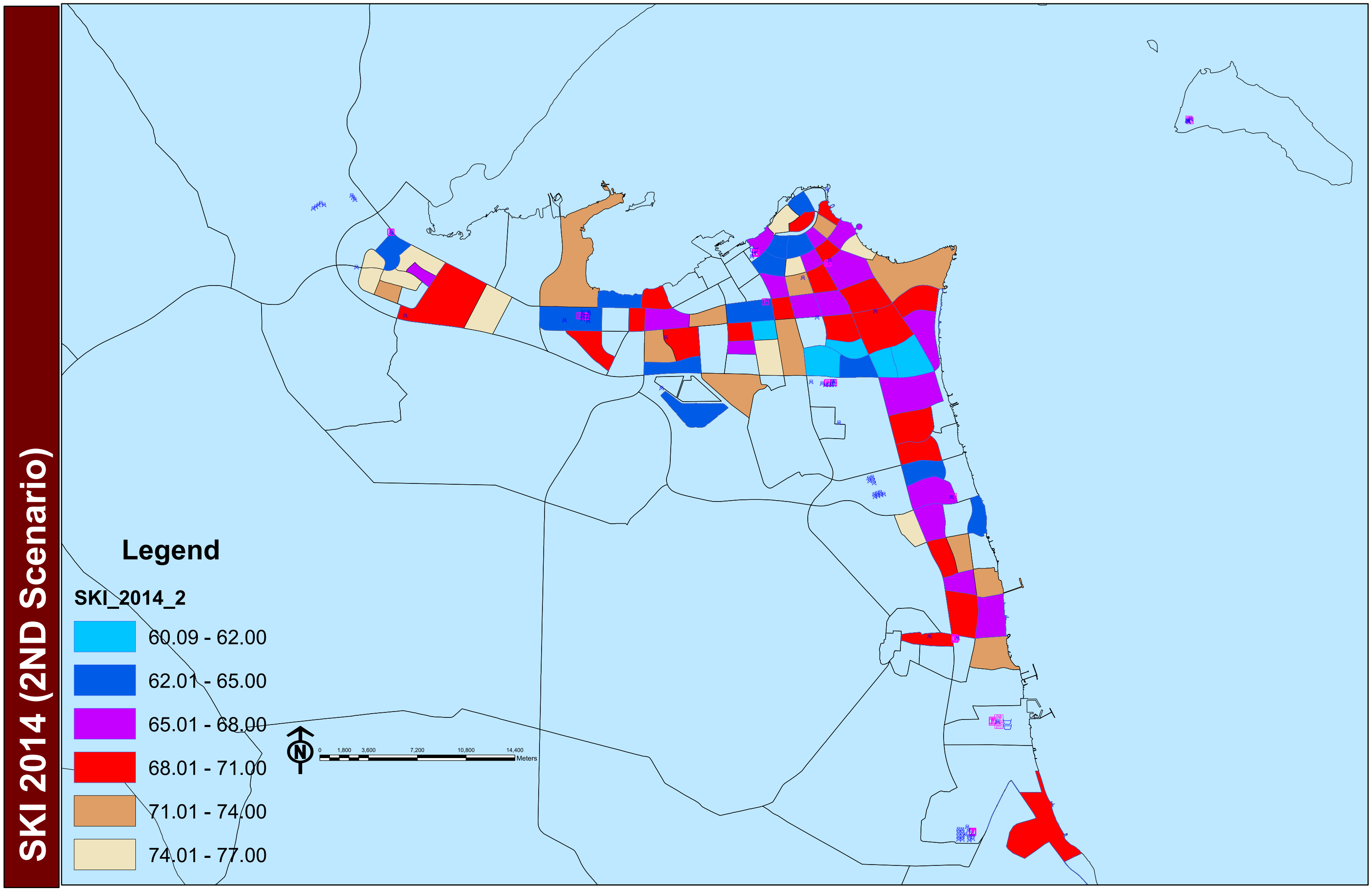

SKI 2016 (1ST Scenario)
Legend
SKI_2016_1
59.70 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
71.01 - 74.00
74.01 - 77.00
N
0
1,800
3,600
7,200
10,800
14,400
Meters

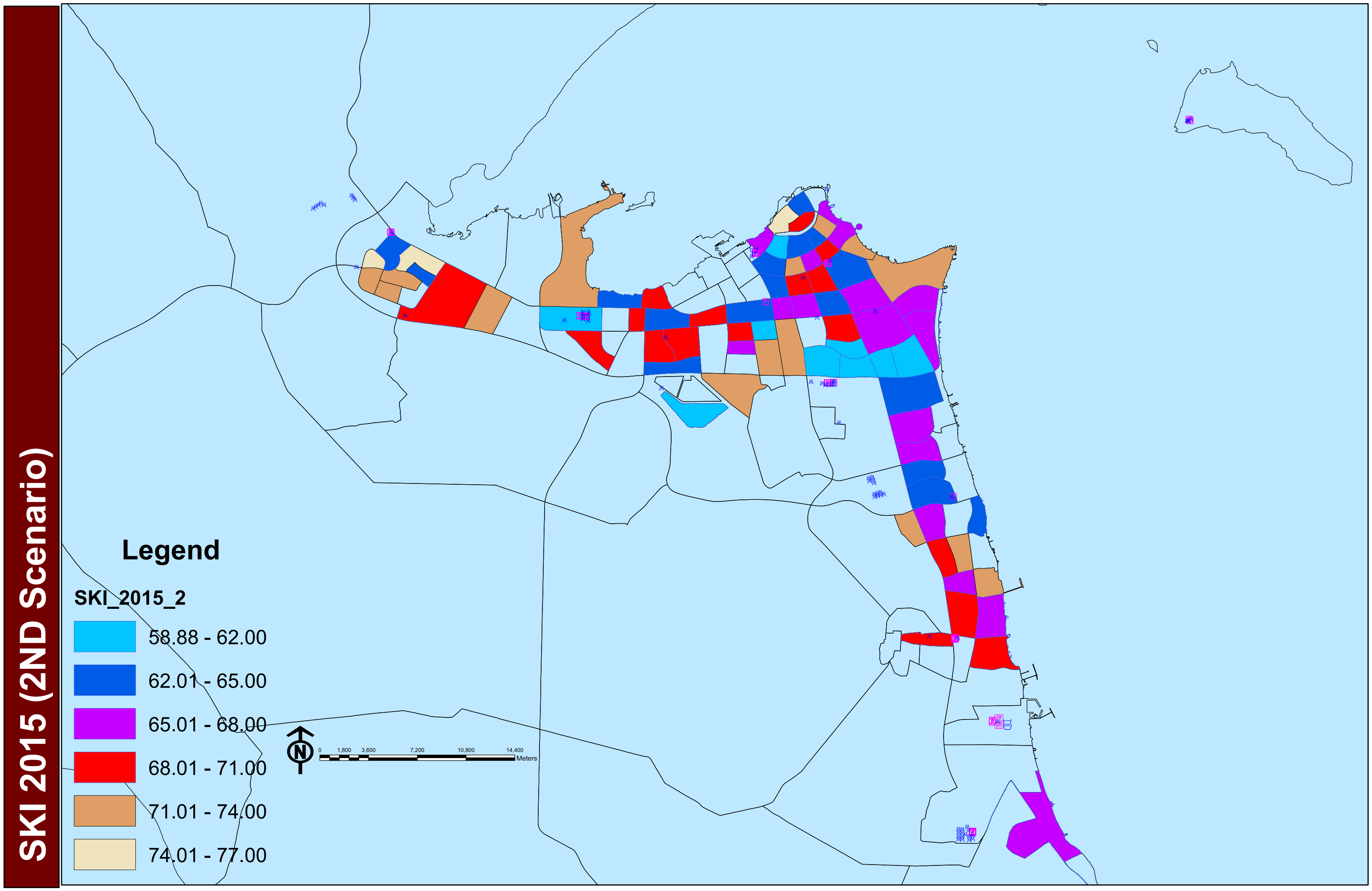


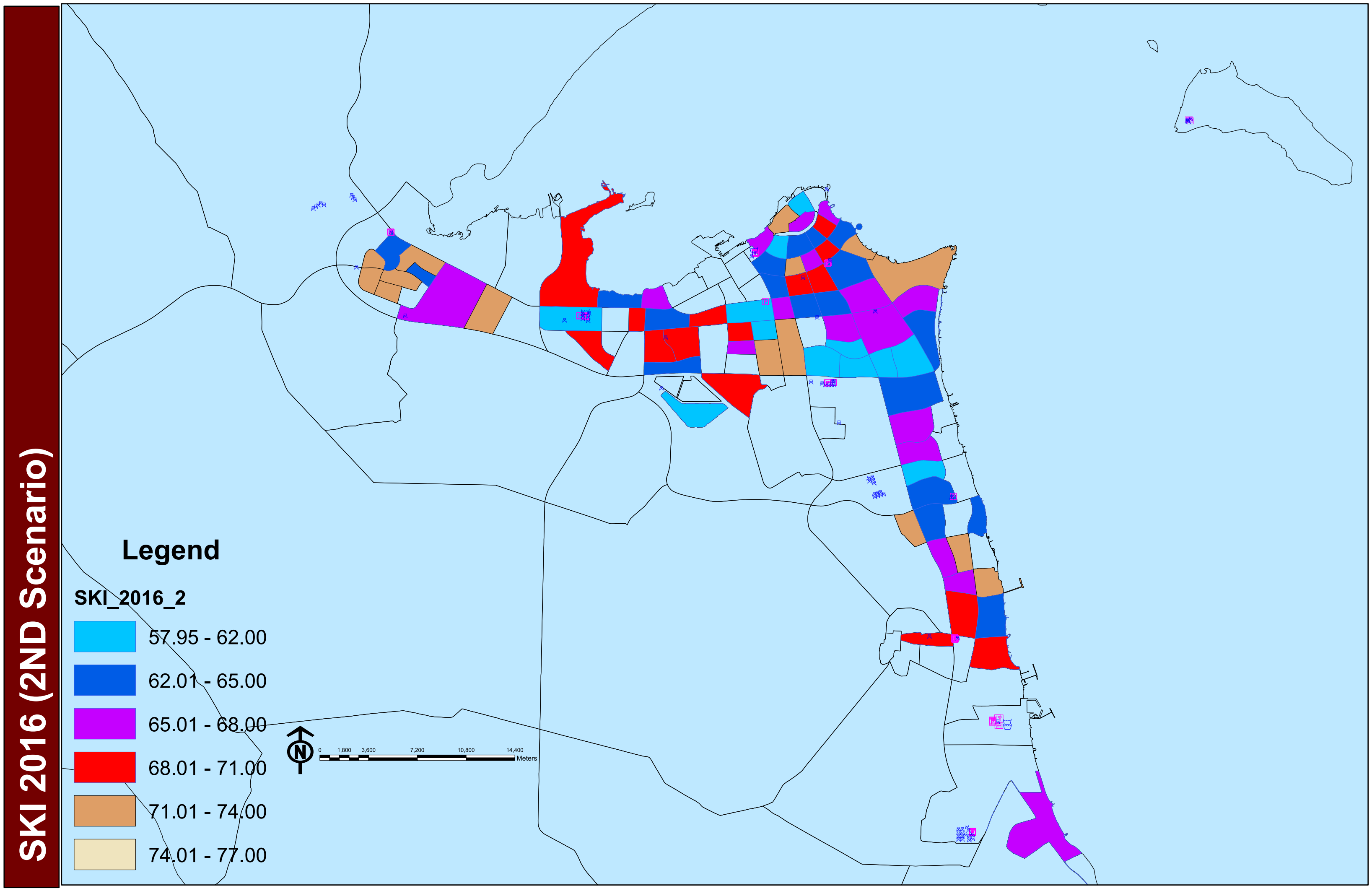
SKI 2017 (1ST Scenario)
Legend
SKI_2017_1
58.47 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
71.01 - 74.00
74.01 - 77.00
N
0
1,800
3,600
7,200
10,800
14,400
Meters

8.4. **2nd Scenario (2013-2017):**

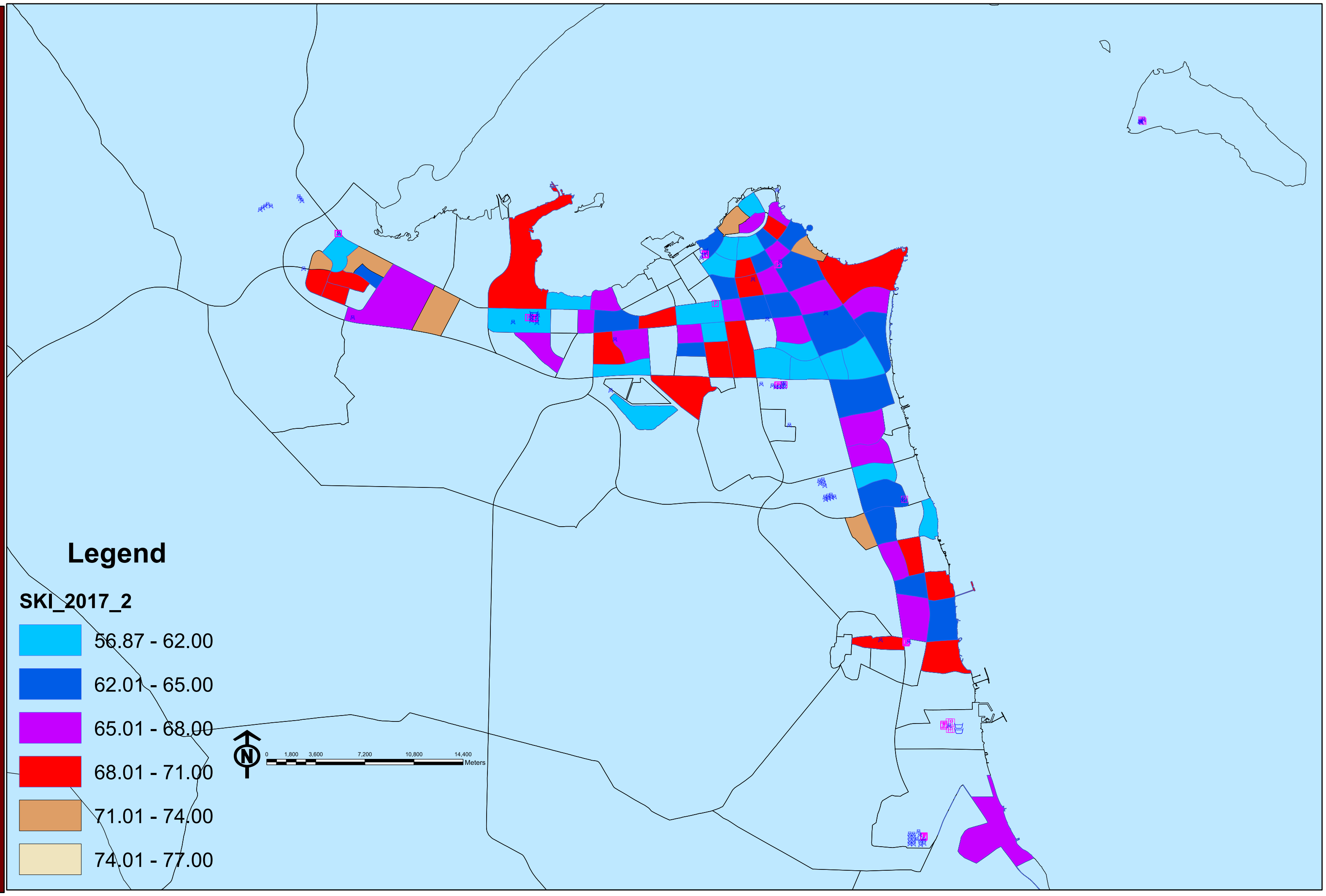



SKI 2014 (2ND Scenario)
Legend
SKI_2014_2
60.09 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
71.01 - 74.00
74.01 - 77.00
N
0
1,800
3,600
7,200
10,800
14,400
Meters


SKI 2015 (2ND Scenario)
Legend
SKI_2015_2
58.88 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
71.01 - 74.00
74.01 - 77.00
N
Meters


SKI 2016 (2ND Scenario)
Legend
SKI_2016_2
57.95 - 62.00
62.01 - 65.00
65.01 - 68.00
68.01 - 71.00
71.01 - 74.00
74.01 - 77.00
N
0 1,800 3,600 7,200 10,800 14,400
Meters

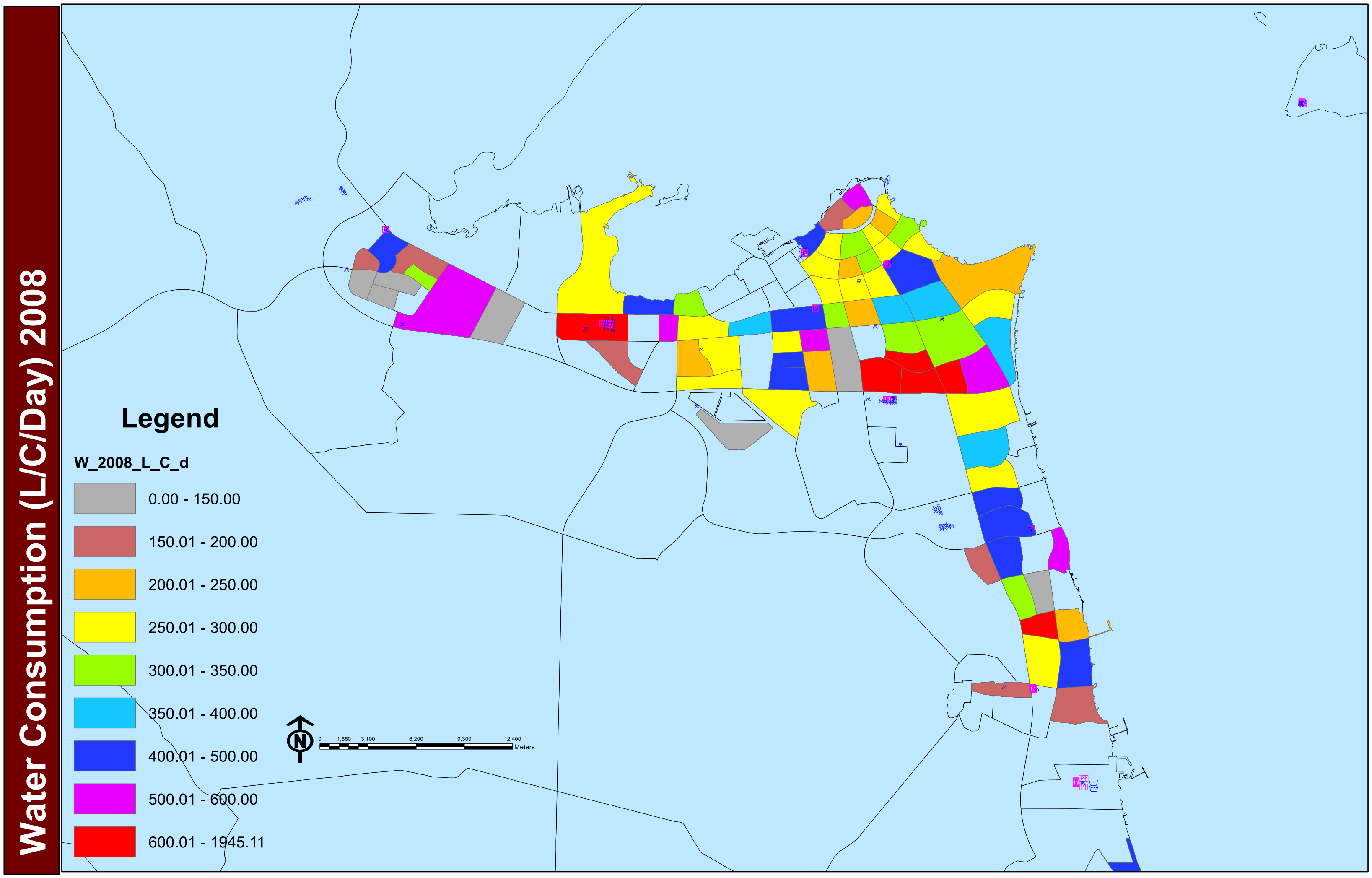
SKI 2017 (2ND Scenario)



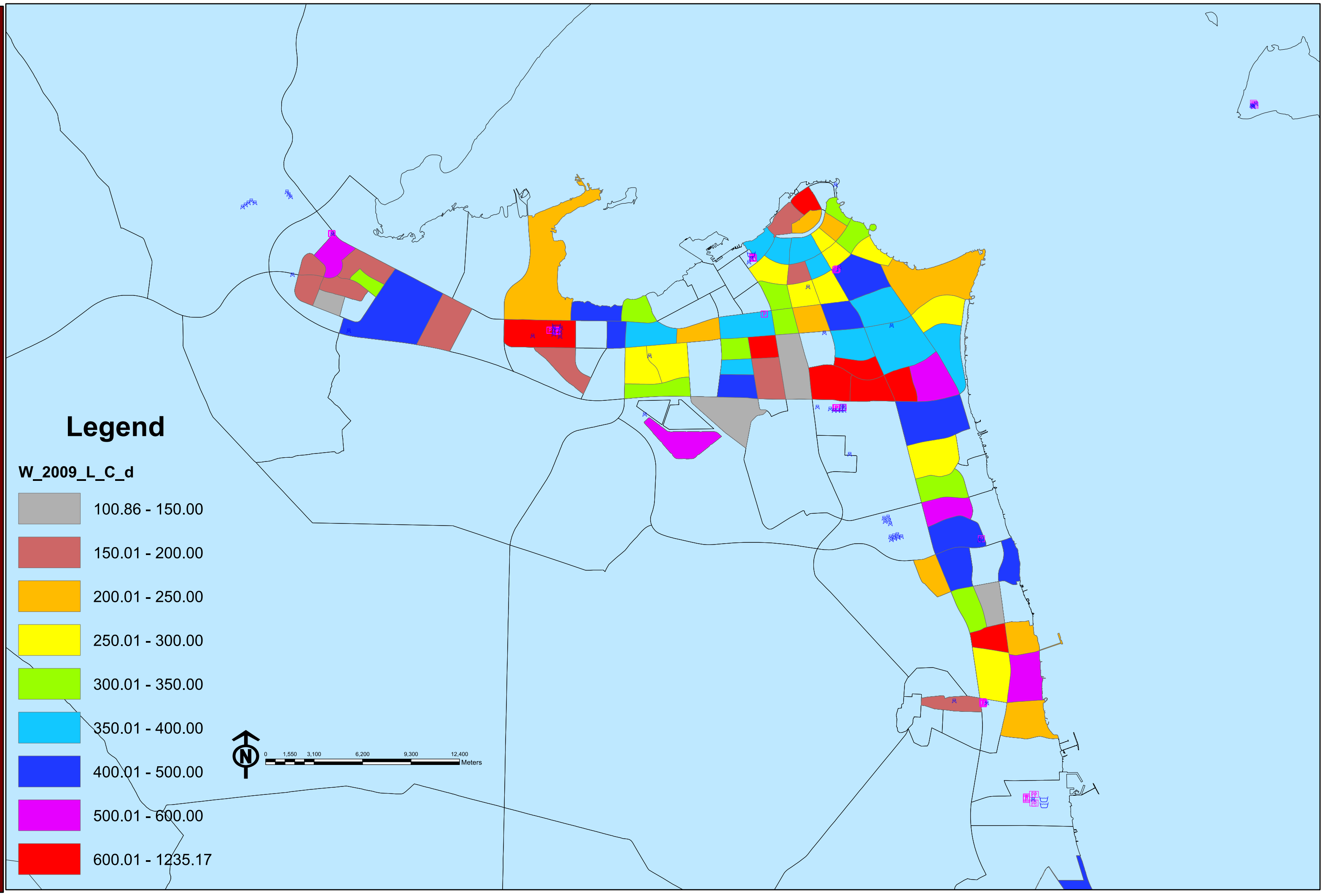
CHAPTER 9: Appendix C:

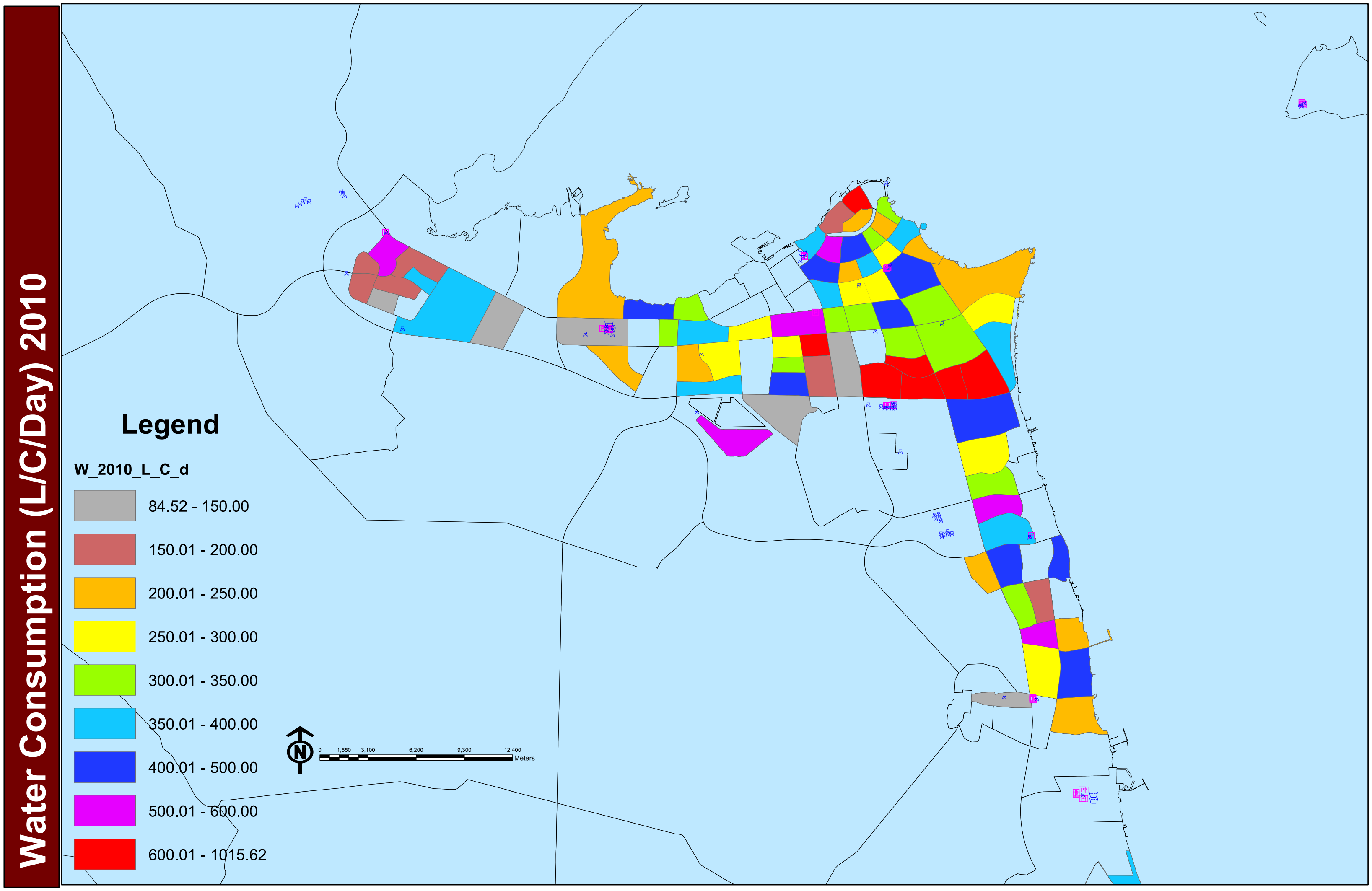
Water consumption per capita (Liter/Capita per day) results for urban areas in Kuwait between 2008 and 2017 under 3 scenarios for water price

9.1. Current water price (2008-2012)

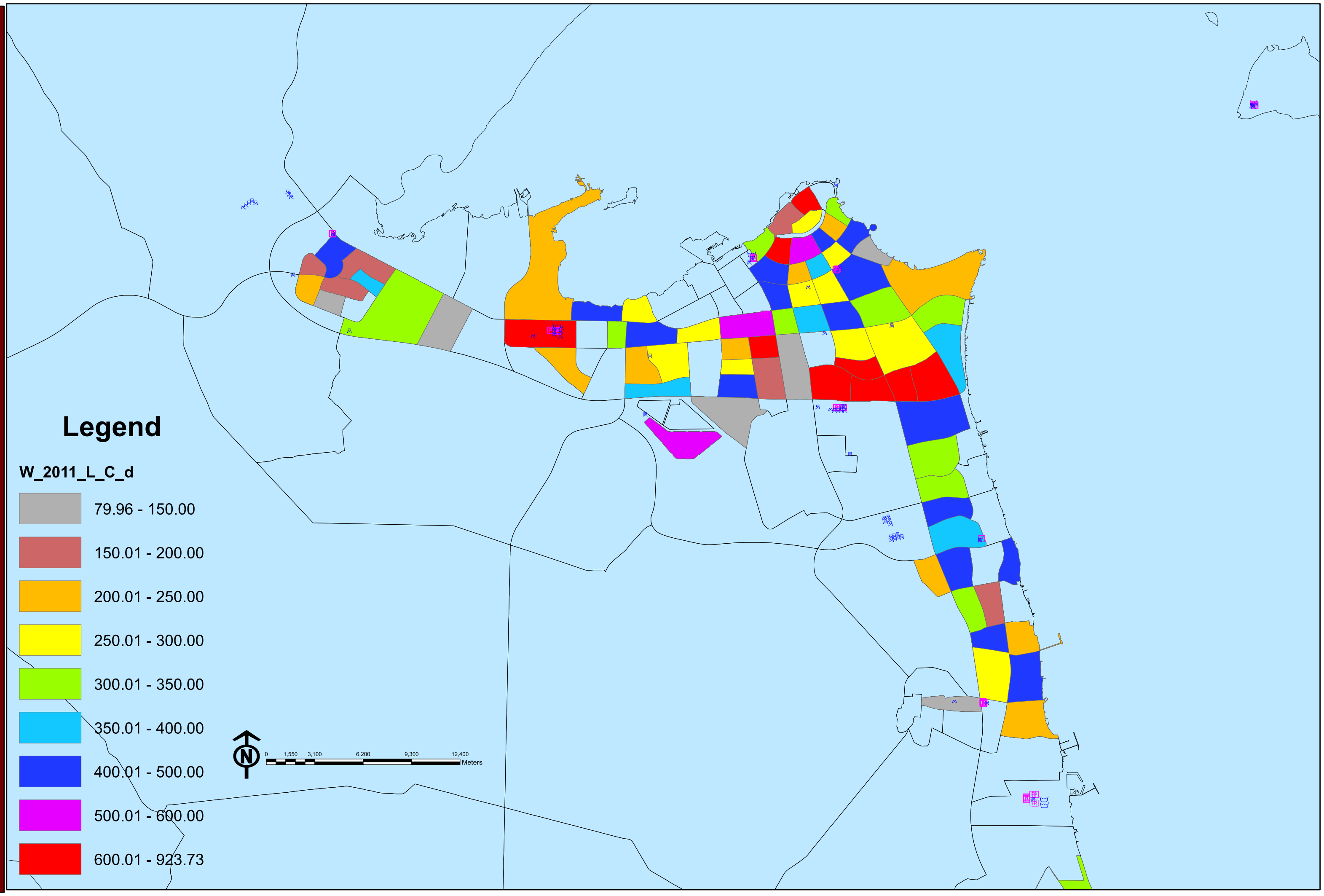


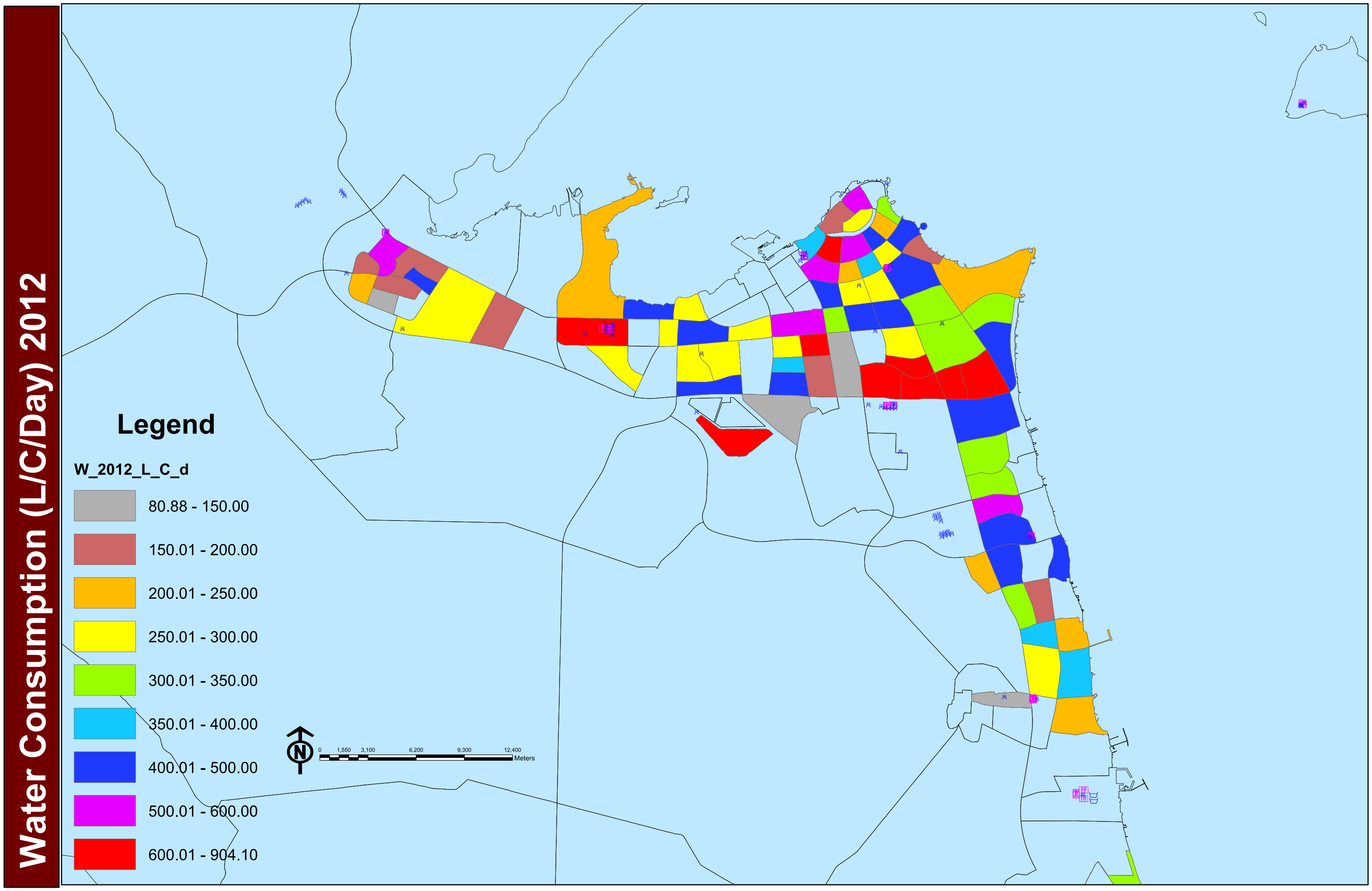
Water Consumption (L/C/Day) 2009




Water Consumption (L/C/Day) 2010
Legend
W_2010_L_C_d
84.52 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 1015.62
N
0 1,550 3,100 6,200 9,300 12,400
Meters

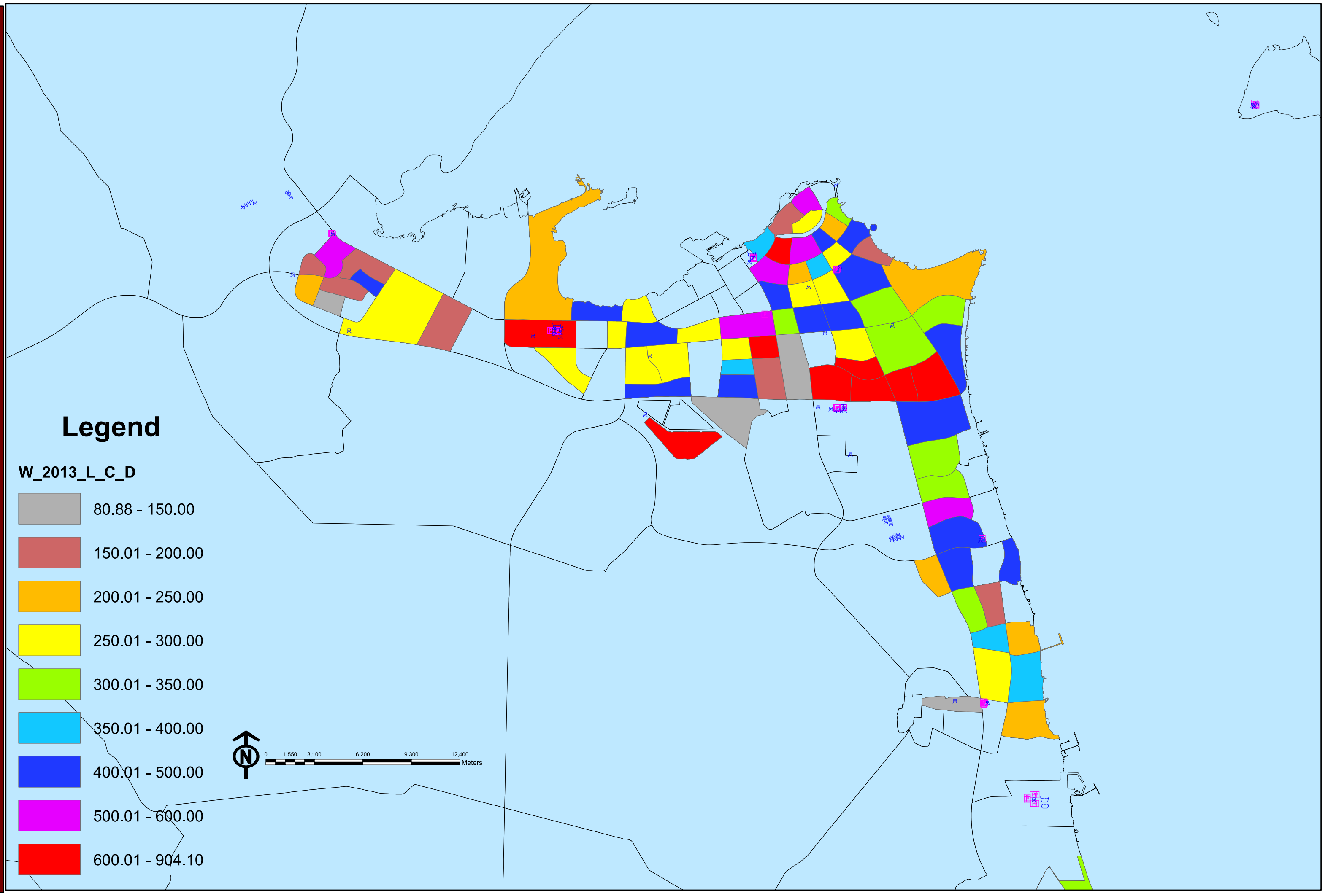
Water Consumption (L/C/Day) 2011





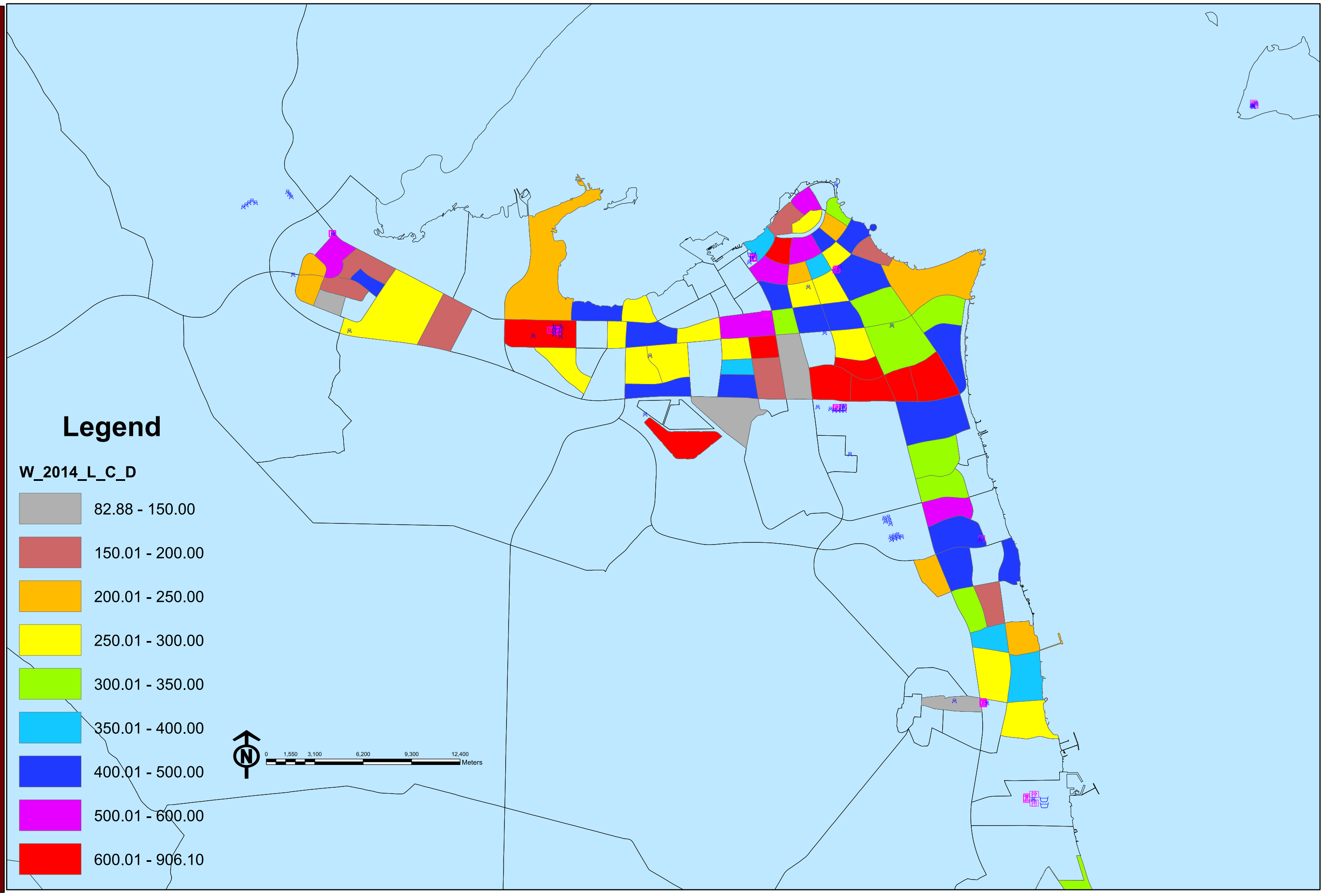
Water Consumption (L/C/Day) 2012
Legend
W_2012_L_C_d
80.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 904.10
N
0 1,550 3,100 6,200 9,300 12,400
Meters

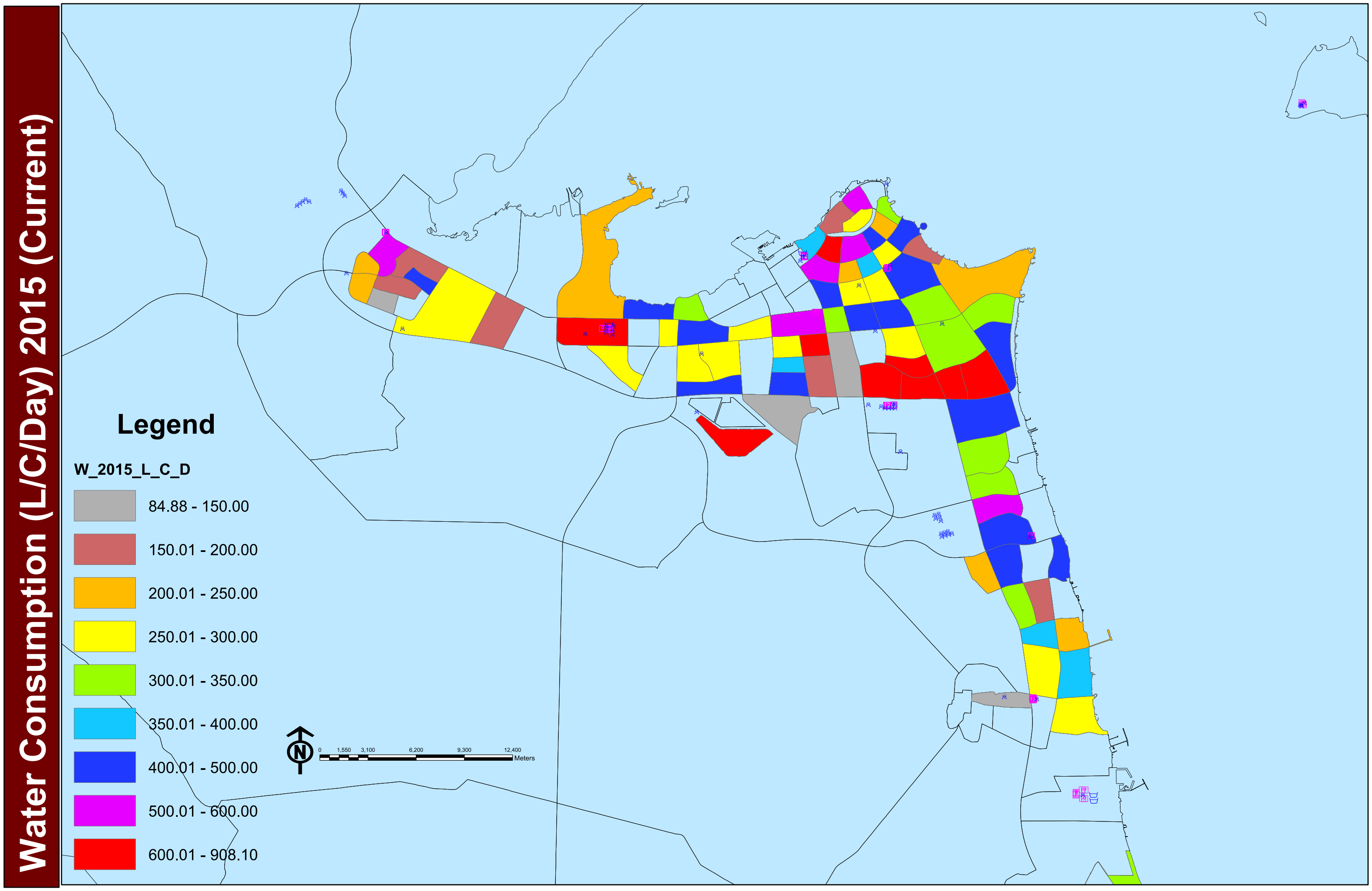
9.2. Current Scenario (2013-2017):



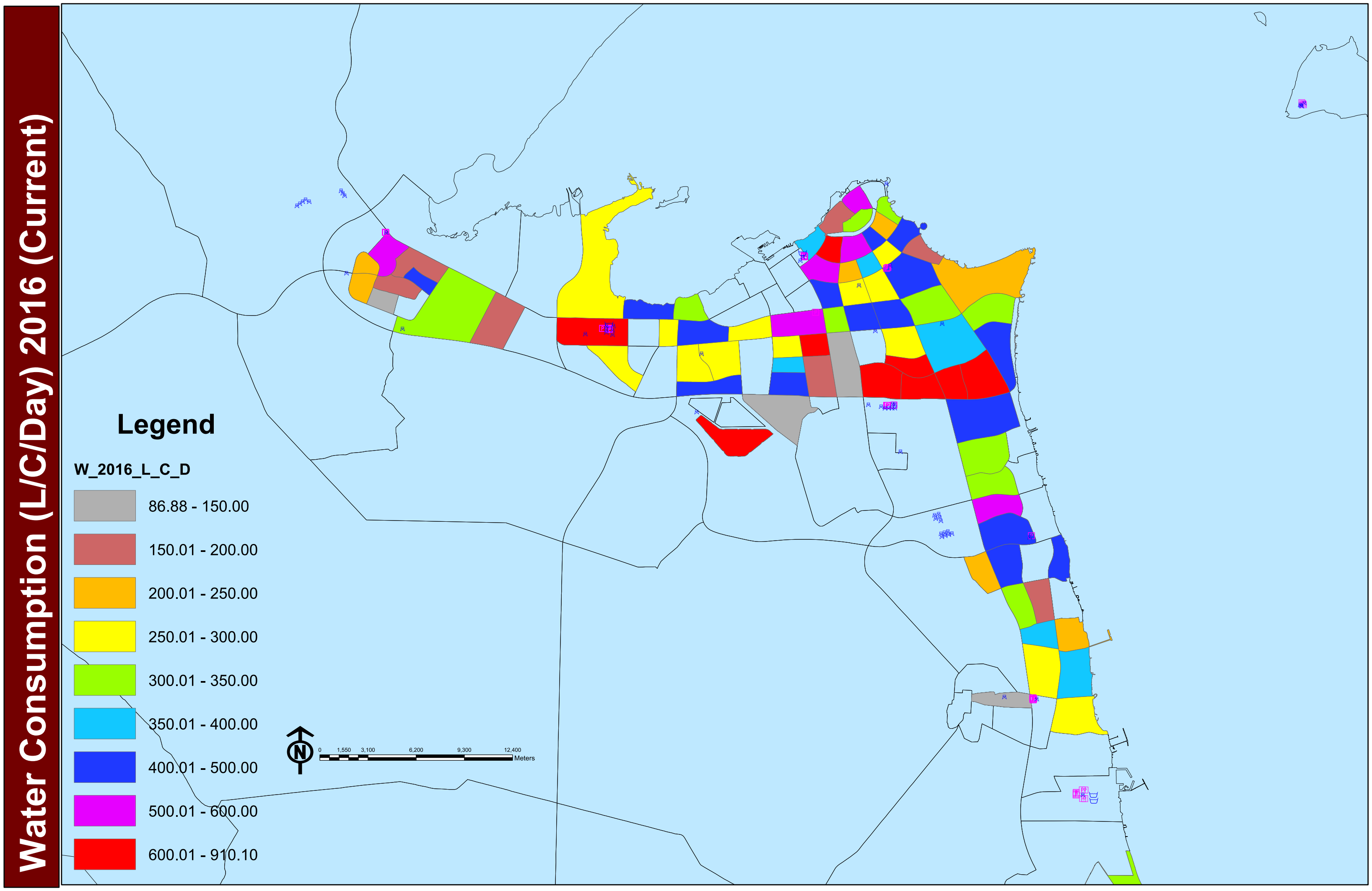
Water Consumption (L/C/Day) 2013 (Current)

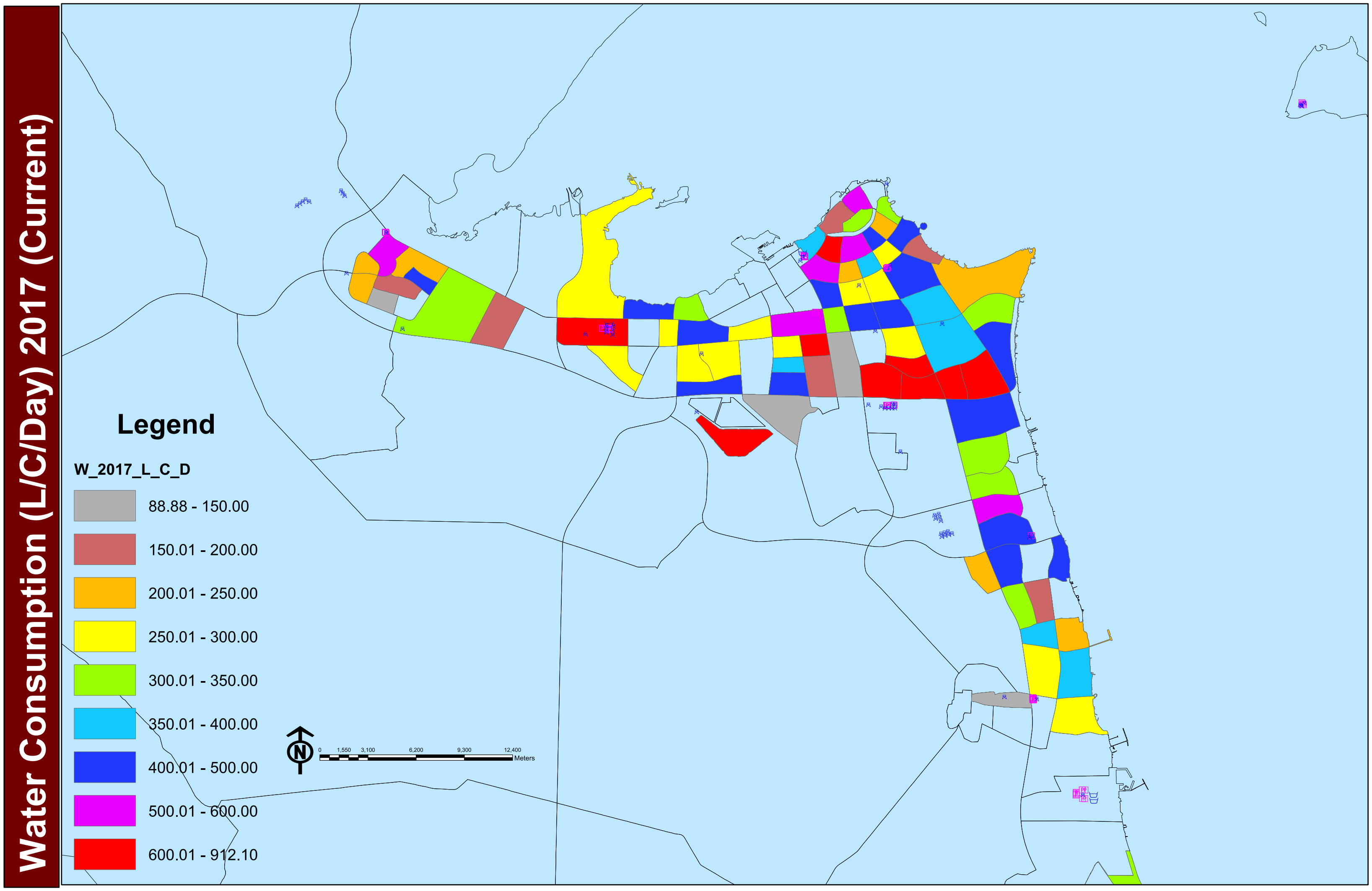
Water Consumption (L/C/Day) 2014 (Current)





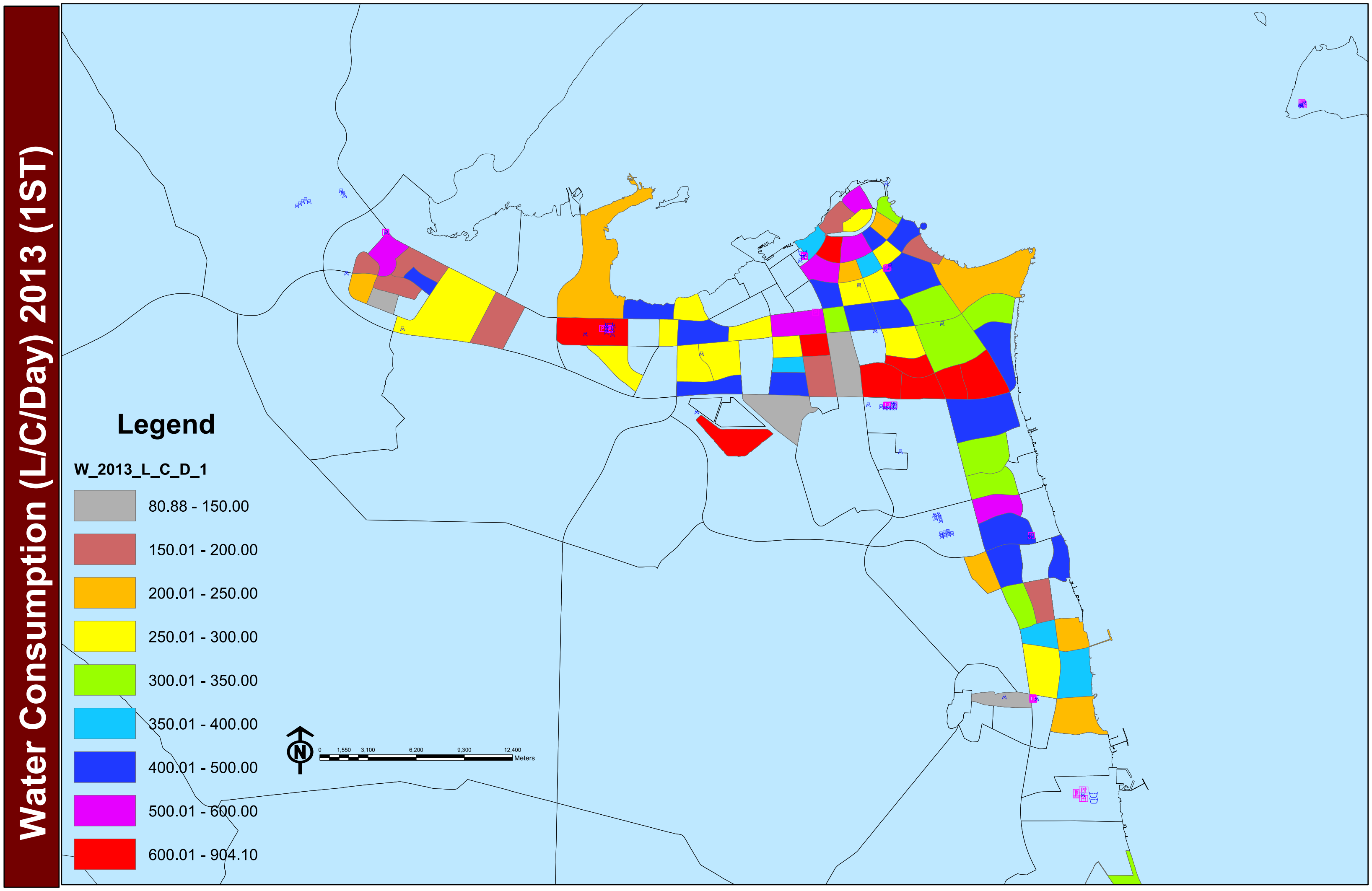
Water Consumption (L/C/Day) 2015 (Current)
Legend
W_2015_L_C_D
84.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 908.10
N
0
1,550
3,100
6,200
9,300
12,400
Meters


Water Consumption (L/C/Day) 2016 (Current)
Legend
W_2016_L_C_D
86.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 910.10
N
0
1,550
3,100
6,200
9,300
12,400
Meters

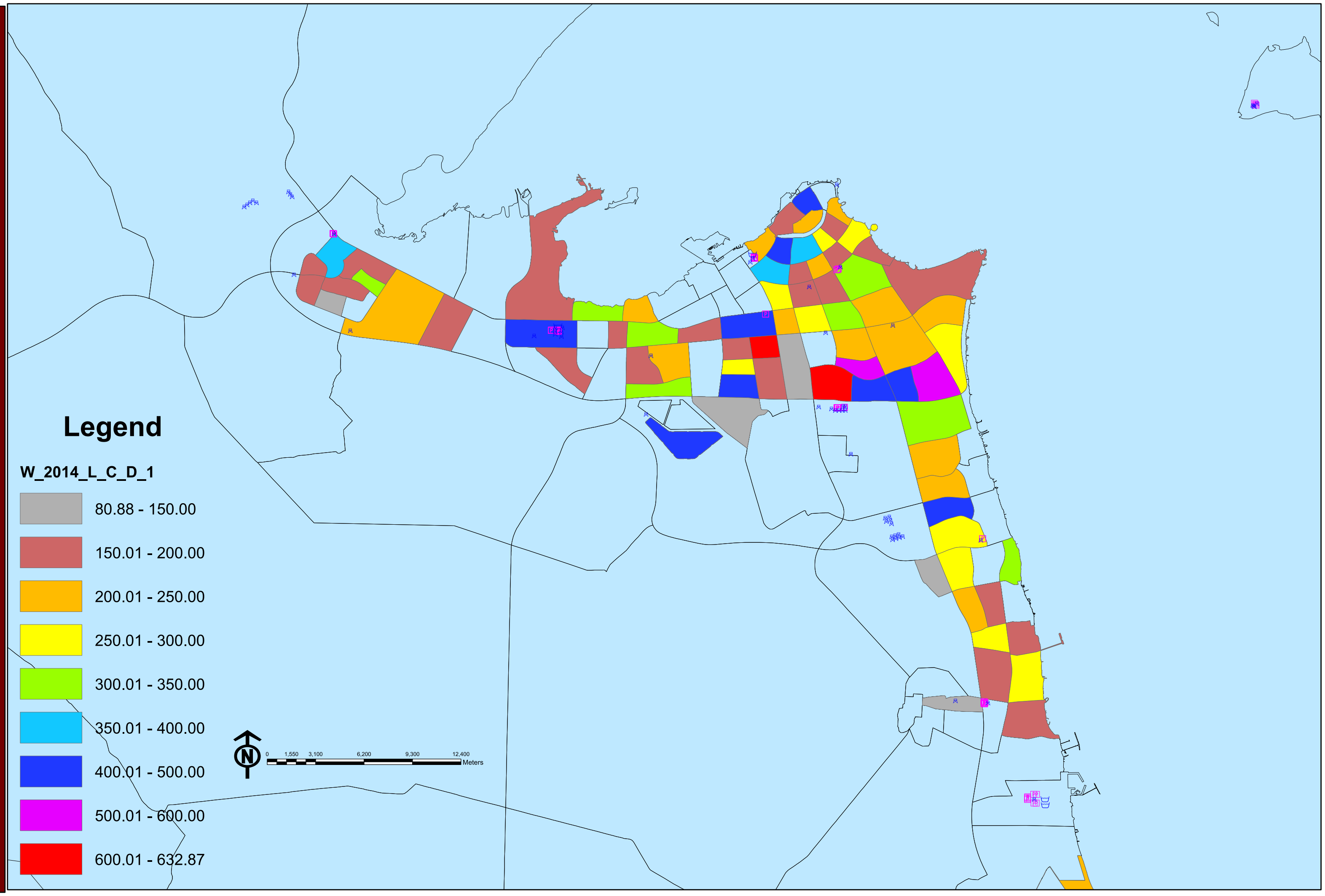


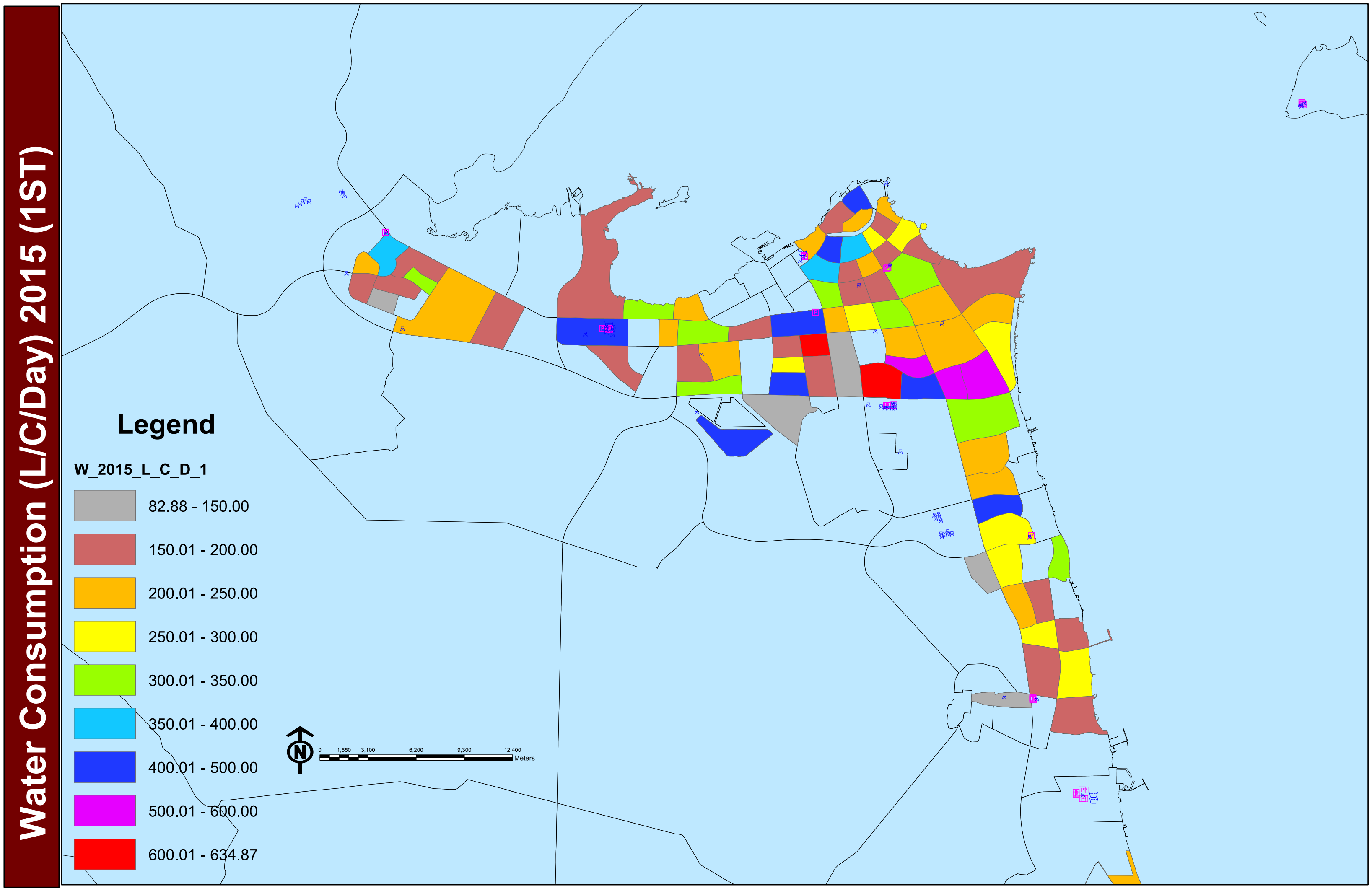
Water Consumption (L/C/Day) 2017 (Current)
Legend
W_2017_L_C_D
88.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 912.10
N
0
1,550
3,100
6,200
9,300
12,400
Meters

9.3. 1st Scenario (2013-2017):

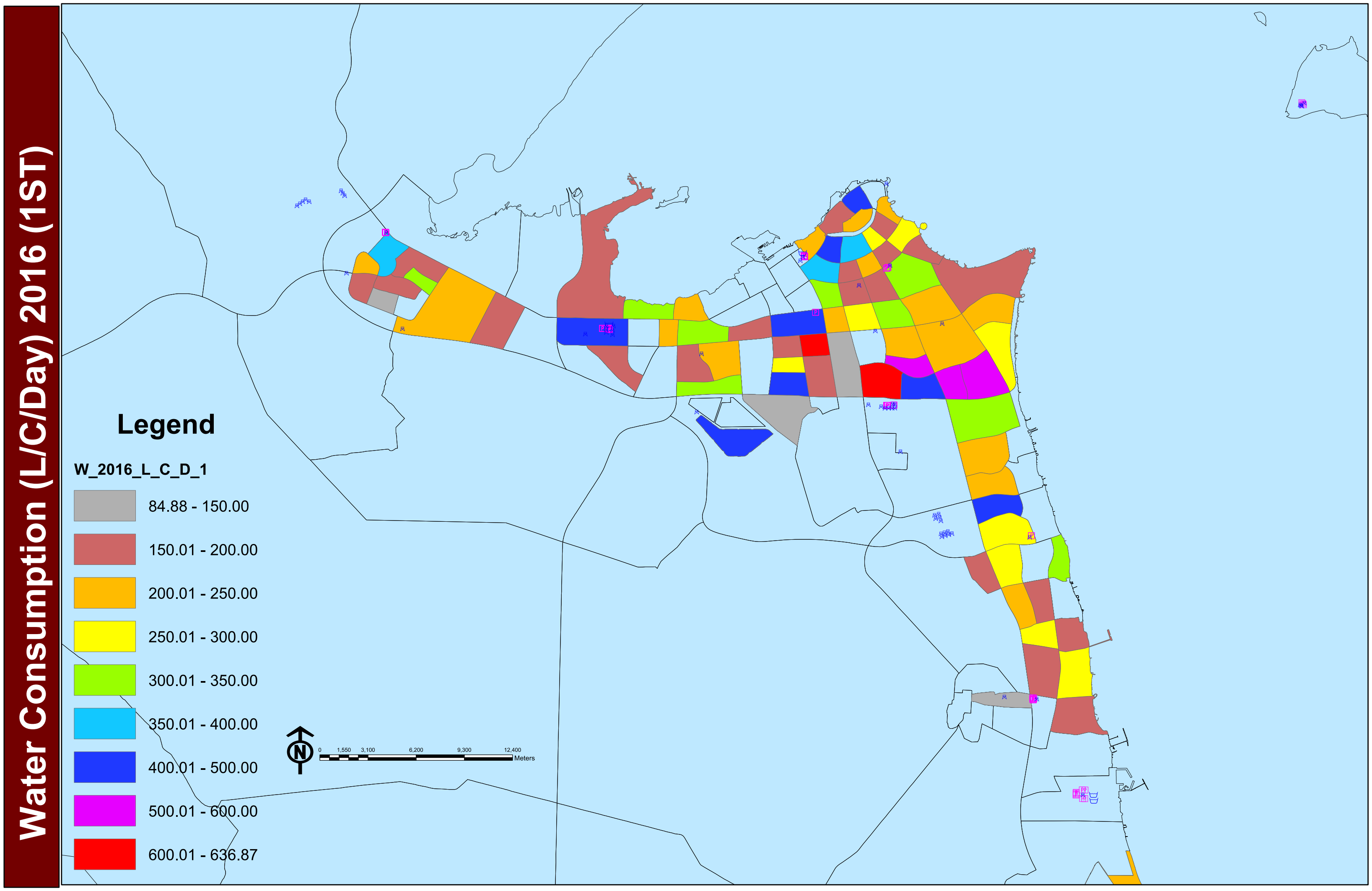


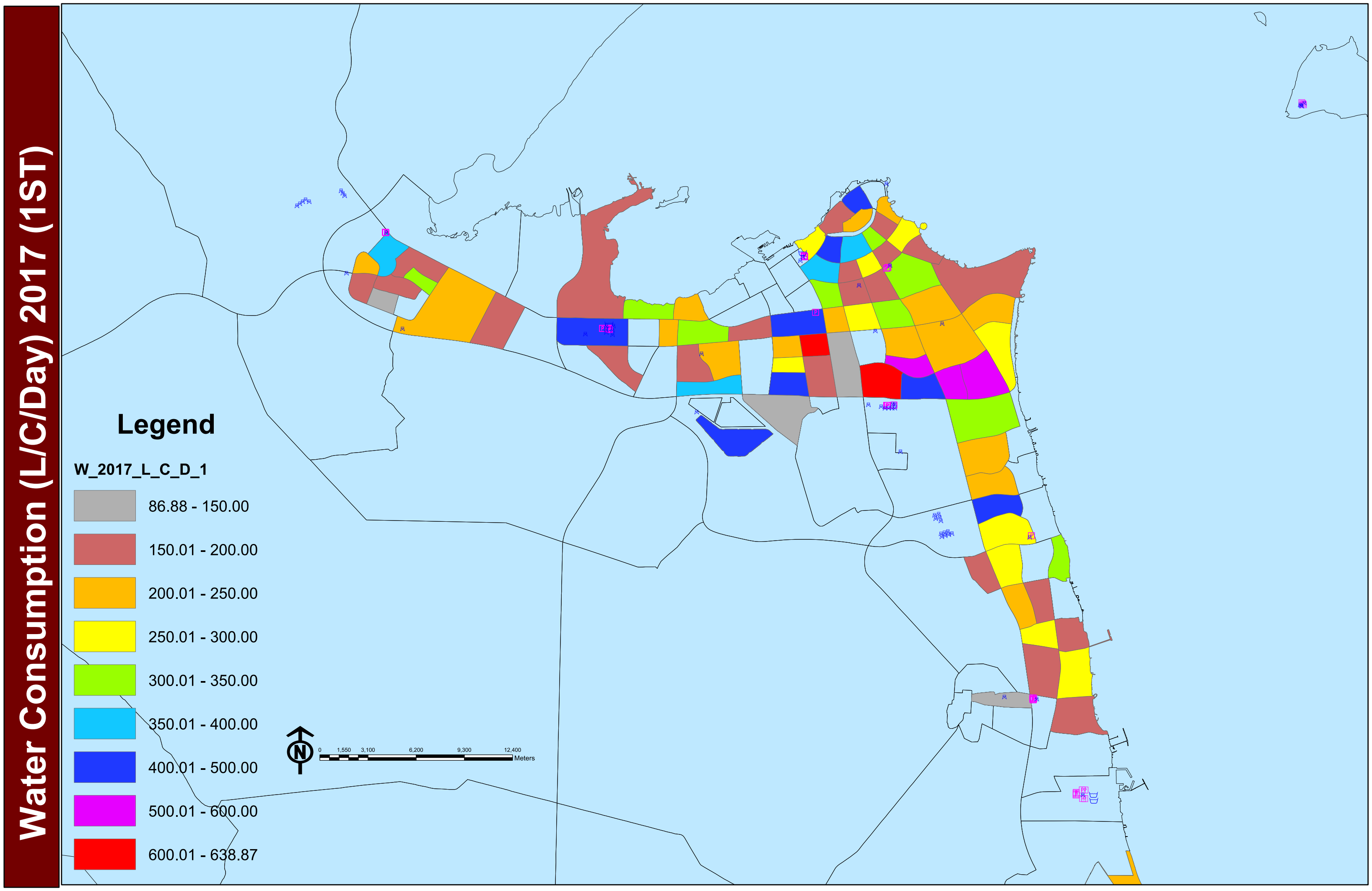
Water Consumption (L/C/Day) 2014 (1ST)



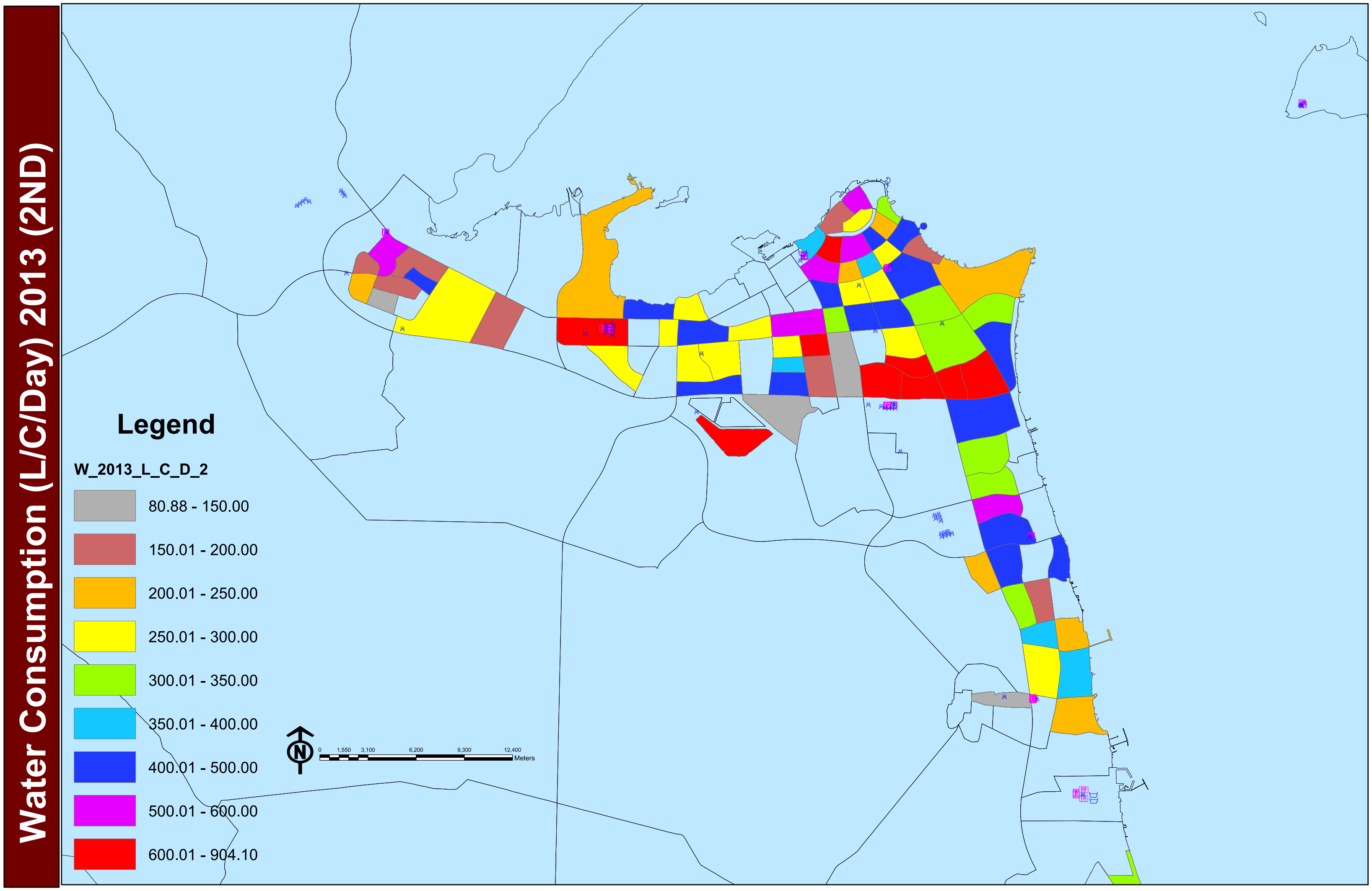


Water Consumption (L/C/Day) 2015 (1ST)
Legend
W_2015_L_C_D_1
82.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 634.87
N
0
1,550
3,100
6,200
9,300
12,400
Meters

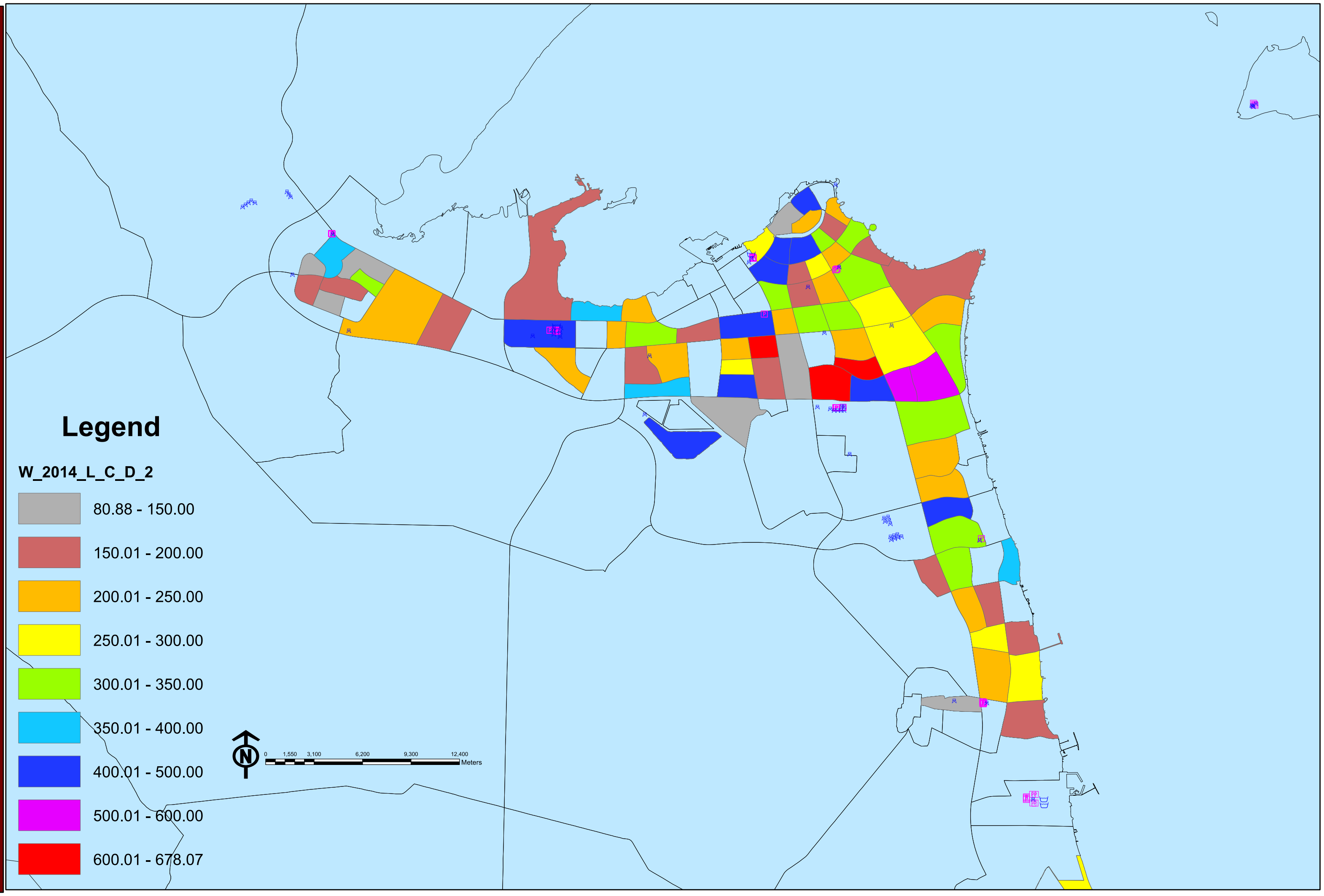

Water Consumption (L/C/Day) 2016 (1ST)
Legend
W_2016_L_C_D_1
84.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 636.87
N
0
1,550
3,100
6,200
9,300
12,400
Meters

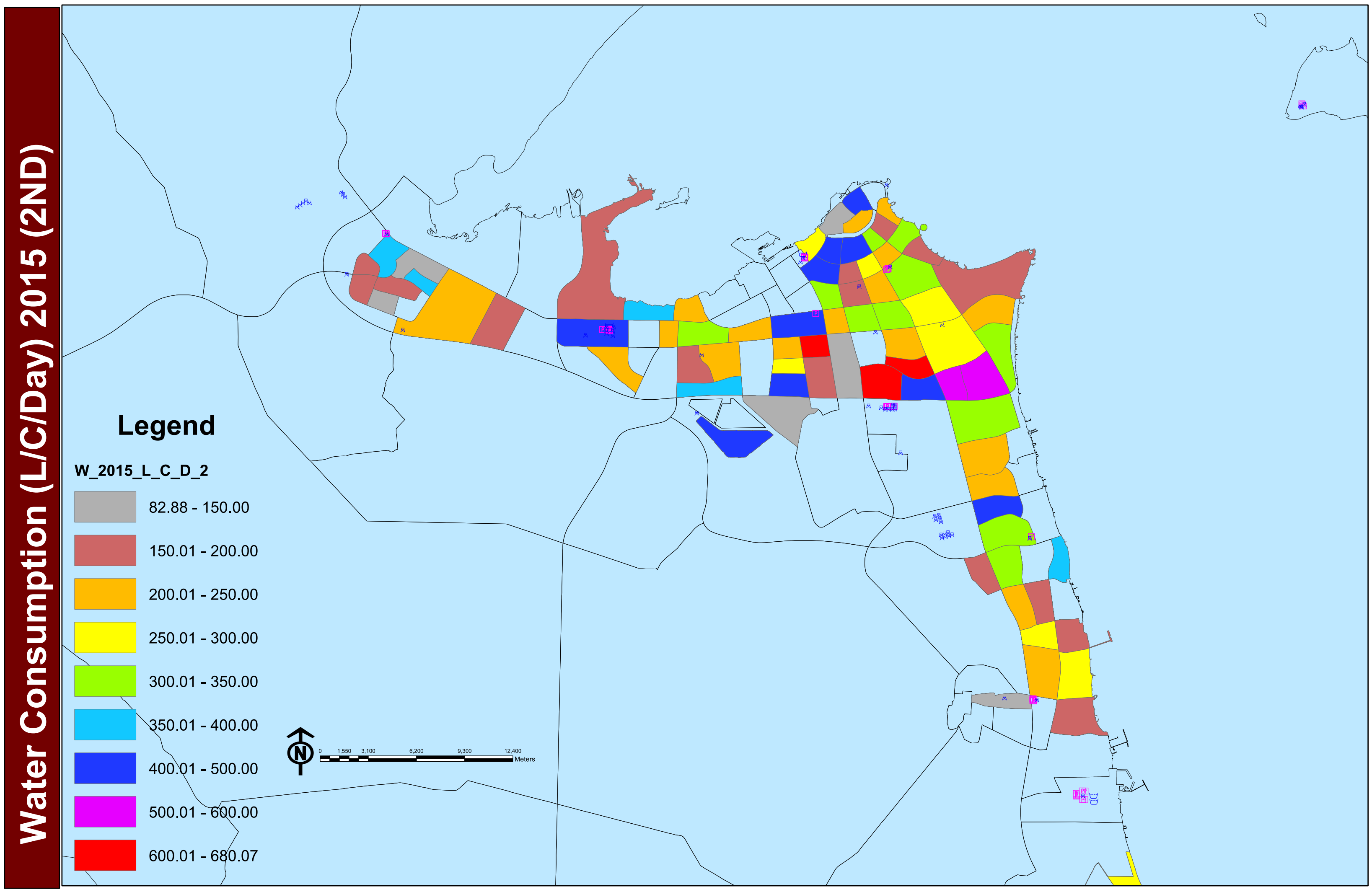

Water Consumption (L/C/Day) 2017 (1ST)
Legend
W_2017_L_C_D_1
86.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 638.87
N
0 1,550 3,100 6,200 9,300 12,400
Meters

9.4. 2nd Scenario (2013-2017):

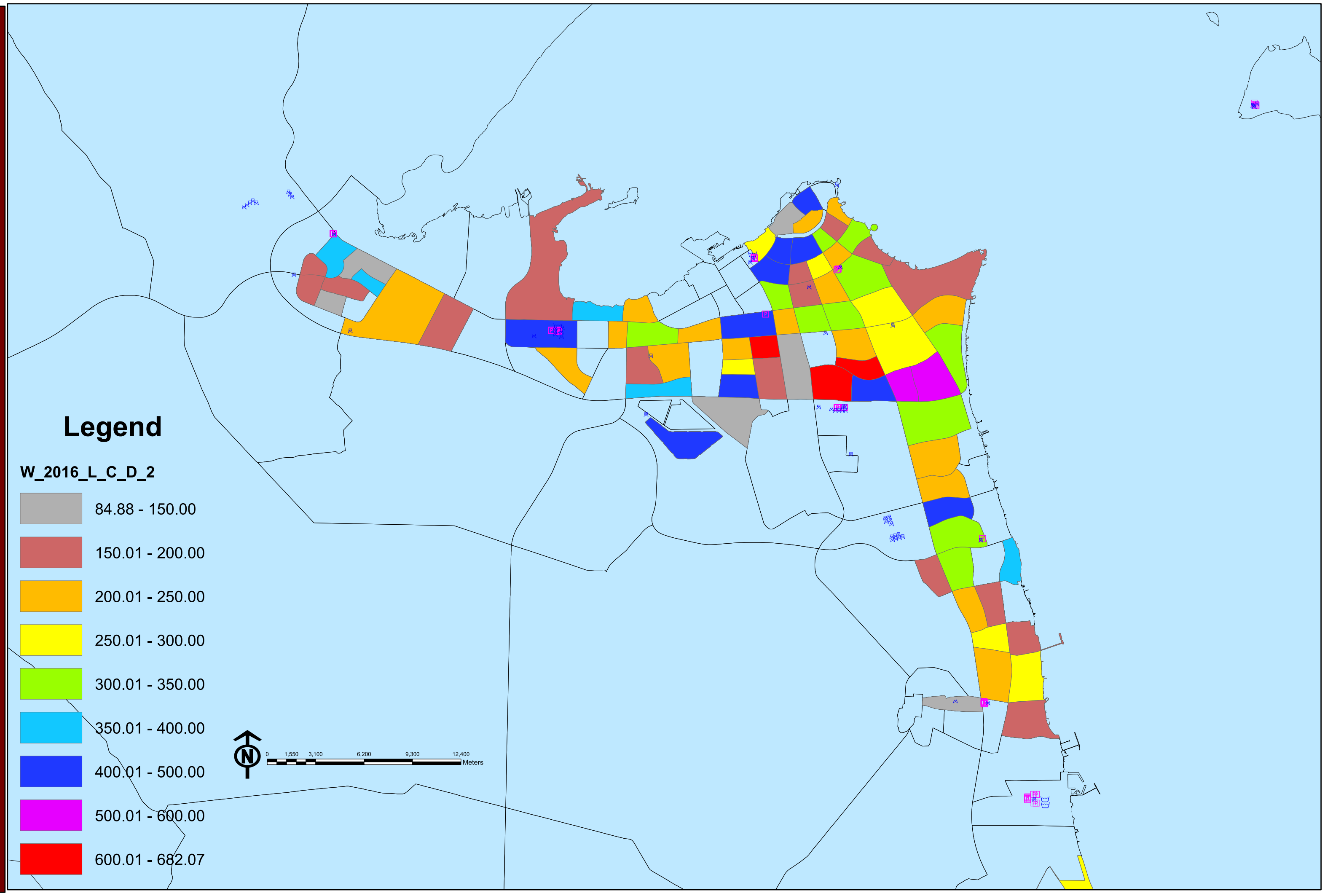


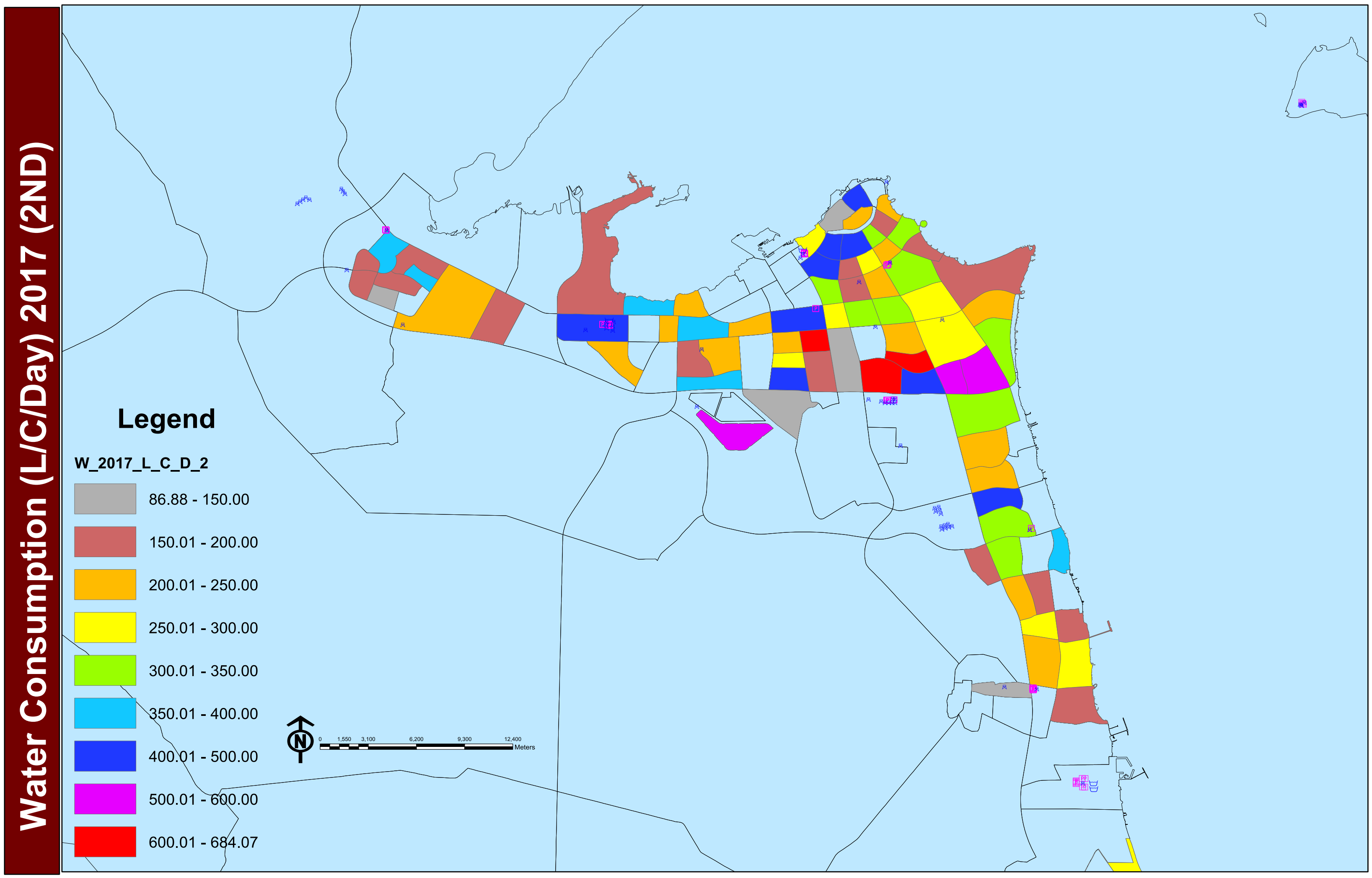
Water Consumption (L/C/Day) 2014 (2ND)




Water Consumption (L/C/Day) 2015 (2ND)
Legend
W_2015_L_C_D_2
82.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 680.07
N
0
1,550
3,100
6,200
9,300
12,400
Meters

Water Consumption (L/C/Day) 2016 (2ND)




Water Consumption (L/C/Day) 2017 (2ND)
Legend
W_2017_L_C_D_2
86.88 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 350.00
350.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 684.07
N
0 1,550 3,100 6,200 9,300 12,400
Meters

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