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Sustainable development of domestic water supply in emerging megacities: The case of the city of Guadalajara, Mexico.

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by

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Die Auswertung der Nachhaltigkeit in der häuslichen Trinkwasserversorgung in aufstrebenden Millionenstädten: Am Beispiel der Stadt Guadalajara, Mexiko.

Von der Fakultät für Umweltwissenshaften und Verfahrenstechnik der Brandenburgischen Technischen Universität Cottbus zur Erlangung des akademischen Grades eines Doktors der Philosophie (Ph.D.) in Umweltwissenchaften genehmigte Dissertation

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Abstract

Water is a primordial resource for the development of urban agglomerations. Today, 50% of the population worldwide is concentrated in urban settlements and 10 - 20% of all worldwide freshwater consumption occurs in the domestic sector (UN: World water development report 3). By 2030, 60% of the world's population will be living in urban settlements (UNESCO), and domestic freshwater consumption will rise by 70% in 2025. Urban areas inflict high pressure on the local and even regional water sources, since the high population density requires large flow volumes in a restricted area, with often competing pressures on the water resource per se as well as for the space needed for water storage or aquifer recharge. This becomes complicated and even critical in areas where natural water availability is already scarce and urban demand is high due to large population sizes. Today 700 million people in 43 countries are living in water stress condition (Human Development Report 2006). Mexico, ranking 88 on a global scale in water availability per capita, is a clear example of this situation, where the most populated urban settlements, such as Mexico City, Monterrey, Guadalajara, Puebla or Queretaro are located in regions which concentrate only 31% of the renewable water of the country (CONAGUA). Thus, the main question arises: How will the urban settlements develop a sustainable water supply now and in the future?

The city of Guadalajara, in particular, has seen an extremely fast and chaotic development in the past three decades, where the population of the city increased from 1,354,000 inhabitants in 1970 to 4,064,000 in 2005; by 2020 Guadalajara is expected to overpass the 5 million inhabitants thus becoming a megacity. Nowadays, overall water consumption in the city is about 9.3 m3/sec. and it is estimated to be 10.3 m3/sec by 2030, with Lake Chapala as the main water source, supplying 55% of the water demand. However, Lake Chapala has been confronted with several severe droughts which critically lowered its water table as was the case between 1998 and 2003 and due to its weak equilibrium droughts could be more recurrent in the future. As the water supply of Guadalajara is strongly linked to the faith of Lake Chapala, Guadalajara needs to reduce its pressure on the lake by adopting strategies based on sustainable development.

The main goal of this research is to provide governments and decision makers with a robust tool that integrates the most amount of information possible but presents this information in a simple way, offering at the same time the possibility to detect the factors that need to be addressed in order to reach sustainability.

The specific aim is to test the use of composite indices (CIs) to the case of the city of Guadalajara in the period of the year 2000 to 2009. CI is a holistic methodology in which independent variables can be aggregated into a single result. CIs thus allow for the comparison between different cases, the integration of qualitative and quantitative variables and the easy use by decision makers. We used 11 carefully selected variables from all three sectors of sustainability, economical, ecological and social, which were first normalized using ranging procedures and process capability indices, and aggregated by using the weighted geometric mean. A set of best strategies Guadalajara should follow are suggested in order to have a sustainable water supply in the future.

With this study, we have been able to show that CIs are an effective tool for evaluating sustainability of domestic freshwater supply at local scale. Overall, Guadalajara reached a CI of 0.29 showing, that its domestic water supply is currently not sustainable. It was able to identify the following three main problems: a) lack of wastewater treatment with just less than 3% of the waste water being treated; b) water loss in the distribution system, with 34% of the water extracted being lost at some point in the distribution system (during treatment, in the pipelines and dweller connection to the distribution net); c) water availability, with increased flow volumes of Lake Chapala in the last six years, but only surpassing its natural storage twice (2004 and 2009). Nonetheless, a clear trend of continuous improvement could be seen overall in the past years with a decline in the domestic water consumption per capita to levels comparable to the one in Berlin, as a consequence of people awareness after the several drought Lake Chapala suffered in the beginning of the decade, and an increase in the level of access to piped water and connectivity to the drainage system to 94% of the city's coverage in 2009 (on year 1990, the access to piped water was 89% and the connectivity to the drainage system was 92%).

Key words: Sustainable development, composite indices, metropolitan zone of Guadalajara, process capability indices, domestic water supply.

Abstract

Wasser zählt zu den wichtigsten Ressourcen in der Entwicklung von Ortschaften und Städten. Heutzutage konzentriert sich 50 % der Weltbevölkerung in urbanen Niederlassungen und 10 bis 20% des weltweiten Frischwasserverbrauchs entfällt auf den häuslichen Bereich (UN: World water development report 3). Bis 2030 wird 60% der Weltbevölkerung in Siedlungen leben. (UNESCO), und der häusliche Trinkwasserkonsum wird sich bis 2025 um 70% erhöht haben. Urbane Gebiete üben einen starken Druck auf lokale und sogar regionale Wasserressourcen aus, da die hohe Bevölkerungsdichte große Volumina für ein begrenztes Areal beansprucht. Dabei wird oft von mehreren Seiten gleichzeititg Druck auf die Wasserressource als solche so wie auf den Raum für die Wasserspeicherung und das Wiederauffüllen des Grundwasserleiters ausgeübt. Kompliziert und sogar kritisch werden diese Umstände in Gebieten, wo natürliches Wasser in geringen Mengen zur Verfügung steht und der Wasserbedarf wegen einer hohen Bevölkerungsdichte steigt. Heutzutage leben 700 Millionen Menschen in 43 Ländern mit Wasserversorgungsschwierigkeiten (Human Development Report 2006). Ein deutliches Beispiel für diese Situation ist Mexico, das die 88. Stelle auf der weltweiten Skala für Pro-Kopf- Wasserverfügbarkeit einnimmt. Die dicht besiedelsten Städte, wie Mexico-City, Monterrey, Guadalajara, Puebla or Queretaro befinden sich in Gebieten, die nur 31% des erneuerbaren Wassers des Landes aufweisen (CONAGUA). So entsteht die wichtigste Frage: Wie werden die Städte sowohl jetzt wie in der Zukunft für eine nachhaltige Wasserversorgung sorgen?

Besonders die Stadt Guadalajara hat sich innerhalb der drei letzten Dekaden extrem schnell und chaotisch entwickelt. Die Bevölkerung nahm von 1,354,000 Einwohnern im Jahre 1970 auf 4,064,000 im Jahr 2005 zu; man schätzt, dass Guadalajara bis 2020 die Marke von 5 Millionen Einwohnern übersteigen und somit zu den Megastädten zählen wird. Heutzutage beläuft sich der durchschnittliche Wasserkonsum auf ca. 9,3 m3/Sek. und man rechnet bis 2030 mit einer Steigerung auf 10,3 m3/Sek. Der Chapala See, der die wichtigste Wasserquelle darstellt und 55% des Wasserbedarfs der Stadt liefert, hat mehrere schwere Trockenperioden durchlitten, die seinen Wasserspiegel deutlich gesenkt haben, z.B. zwischen den Jahren 1998 and 2003. Dürrezeiten könnten in Zukunft noch häufiger auftreten. Da Guadalajaras Wasserversorgung stark vom Schicksal des Chapala Sees abhängt, muss Guadalajara den Druck auf den See mindern, indem es auf Nachhaltigkeit basierende Strategien anwendet.

Das wichtigste Ziel der vorliegenden Forschungsarbeit besteht darin, Regierungen und Entscheidungsträger mit einem robusten Werkzeug zu versehen, das sowohl die größtmögliche Menge an Informationen auf eine einfache Weise bereitstellt, als auch jene Faktoren hervorhebt, die zur Erlangung von Nachhaltigkeit berücksichtigt werden müssen.

Das spezifische Ziel liegt darin, die Anwendbarkeit von Gesamtindexes (CIs) für die Stadt Guadalajara in der Zeit von 2000 bis 2009 zu testen. CI ist eine holistische Methodologie, bei der unabhängige Variablen einem einzigen Ergebnis hinzugefügt werden können. Somit ermöglichen die CIs den Vergleich zwischen unterschiedlichen Fällen, die Inbezugnahme von qualitativen und quantitativen Variablen und die einfache Anwendung durch die Entscheidungsträger. Wir verwendeten 11 mit Bedacht ausgesuchte Variablen aus den drei Bereichen der Nachhaltigkeit, dem wirtschaftlichen, dem ökologischen und dem sozialen, die als erste mittels eines Rangverfahrens, der Indizes für die Anwendbarkeit sowie eines ausgewogenen geometrischen Durchschnitts zur Norm geworden sind. Im Anschluss folgt ein Maßnahmenkatalog für die künftige nachhaltige Wasserversorgung der Stadt Guadalajara.

Mit dieser Untersuchung haben wir bewiesen, dass CIs ein wirksames Werkzeug zur Beurteilung der Nachhaltigkeit der häuslichen Wasserversorgung auf lokaler Ebene sind.

Dabei erreichte Guadalajara ein CI von 0.29, d.h. dass gegenwärtig seine häusliche Wasserversorgung nicht nachhaltig ist. Wir konnten die drei folgenden Hauptprobleme identifizieren: a) Mangel an Abwasserbehandlung, wobei weniger als 3% des Abwassers behandelt werden; b) Wasserverlust im Verteilungssystem, wobei 34% des gelieferten Wassers an verschiedenen Punkten des Verteilungssystems verloren gehen (entweder während der Aufbereitung, in den Rohren oder in den Haushaltsverbindungen zum Verteilungsnetz); c) Wasserverfügbarkeit bei größeren Durchflussmengen vom Chapala See während der letzten sechs Jahre, wobei er nur zweimal seine natürliche Speicherkapazität überstieg (2004 und 2009). Nichtdestotrotz war in den letzten Jahren im Allgemeinen ein ständiger Verbesserungstrend zu beobachten. Der häusliche Pro- Kopf-Wasserverbrauch nahm auf ein mit Berlin vergleichbares Niveau ab, was auf die Bewußtwerdung der Bevölkerung nach mehreren Dürren, die der Chapala See Anfang der Dekade erlitt, zurückzuführen ist und auf die Zunahme der Zugangsmöglichkeiten zu Leitungswasser sowie den Anschluss an das Abwassersystem, das 2009 94% der Stadt erfasste (1990 betrug der Anschluss an das Wasserleitungssystem nur 89% und jener zum Abwassersystem 92%).

Schlüsselwörter: Nachhaltige Entwicklung, Gesamtindexes, Großstadtareal von Guadalajara, Prozessfähigkeitsindizes, häusliche Wasserversorgung.

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Glossary of Symbols and Abbreviations

AHP	-	Analytical Hierarchical Process
BOD_5	-	Biological Oxygen Demand in 5 days.
CDC	-	Centre of Disease Control
CEA	-	Water Council of State of Jalisco
CI	-	Composite Index
COD	-	Chemical Oxygen Demand
COEPO	-	Population Council of the State of Jalisco
CONAGUA	-	National Water Council
CONAPO	-	Population National Council
CWQI	-	Canadian Water Quality Index
DGAPA	-	General Director of Drinking Water and Sewage
DGOSAPA	-	Drinking Water and Sewage System Operation
EF	-	Ecological Footprint
EPA	-	Environmental Protection Agency
EPI	-	Environmental Performance Index
ESI	-	Environmental Sustainability Index
EVI	-	Environmental Vulnerability Index
FA	-	Factor Analysis
GDP	-	Gross Domestic Product
HDI	-	Human Development Index
IFC	-	Interval Scale Full Comparability
IMTA	-	Mexican Institute of Water Technology

INC	-	Interval Scale Non-Comparability
INEGI	-	National Institute of Statistics and Geography
IUC	-	Interval Scale Unit Comparability
LSL	-	Lower Specification Limit
MZG	-	Metropolitan Zone of Guadalajara
NGO	-	Non-Governmental Organization
NTU	-	Nephelometric Turbidity Units
NWL	-	National Water Law
OECD	-	Organization for Economic Co-operation and Development
PCA	-	Principal Components Analysis
PCI	-	Process Capability Indices
PPM	-	Parts Per Million
PRI	-	Revolutionary Institutional Party
PROFEPA	-	Federal Attorney Office of Environmental Protection
RFC	-	Ratio Scale Full Comparability
SAHOP	-	Ministry of Human Settlements and Public Works
SCNM	-	System of National Bill of Mexico
SD	-	Sustainable Development
SEDUE	-	Urban Development and Ecology Ministry
SEMARNAT	-	Mexican Ministry of Environment and Natural Resources
SIAPA	-	Potable Water and Sewage Intermunicipal System
SMN	-	Meteorology National Service
SPC	-	Statistical Process Control

SRH	-	Ministry of Hydric Resources
TDS	-	Total Dissolved Solids
TSS	-	Total Suspended Solids
USD	-	United States Dollars
USL	-	Upper Specification Limit
UV	-	Ultra Violet
WCED	-	World Commission on Environment and Development
WHO	-	World Health Organization
WQI	-	Water Quality Index
WPI	-	Water Poverty Index
WSI	-	Water Sustainability Index
WTP	-	Water Treatment Plant
WWSI	-	Weighted Water Sustainability Index
$\leftrightarrow$	-	If and only if

1. Introduction

Water is needed in all aspects of life and is a key factor in all the species survival, 80 % of all living beings is composed of water. Without it, life would not be possible; therefore, water can be considered one of the most, if not the most, valuable resource on earth. 70 % of the planet's surface is covered by water; however, only 2.53 % is fresh water. The problem is that most fresh water is not available for human consumption: 68.9 % of fresh water is located in glaciers on Greenland and Antarctica, 30.8 % is subterranean water (low deep and deep aquifers), and barely 0.3 % is superficial water (Santos et al. 2004; Carabias et al. 2005).

Around 200,000 km^3 of water is available for human use and to sustain natural ecosystems, with today's population of 6 895 889 000 inhabitants (UN). The theoretical water availability per capita would be 79,000 litres per day (Carabias et al. 2005); which would be enough to satisfy the needs of the actual and future population plus the ecosystems needs.

However, the world is currently facing a water crisis provoked by several factors, of which the following can be mentioned: Available freshwater is not homogeneously distributed over the world; America and Asia contains the most of water with 47 % and 32 % respectively, while Europe, Africa and Oceania contain 21 % altogether; even inside continents water is not equally distributed. An example is Africa, where most of water is concentrated in Central Africa, while the region of Sahara suffers from extreme water scarcity. Scarcity of fresh water is already degrading ecosystems, threatening human health, and limiting agricultural and industrial production, while the possibility of international conflicts is increasing (Postel et al. 1996). Nearly 40 % of the world's population lives in countries with moderate to severe hydric stress, and by 2025 more than 66 % will suffer from water stress conditions (Arnell et al. 1999). A sixth of the population does not have access to drinkable water, and almost 40 % do not have access to sanitation systems. In developed countries, 90 % of the residual water is returned back to water bodies without previous treatment. A great amount of available freshwater is polluted and not suitable anymore for human consumption; currently, according to the World Commission of Water, more than a half of world's major rivers are being seriously depleted and polluted (Carabias et al. 2005).

The same driving factors observed worldwide are also present in Mexico: The north and northeast of Mexico, which represent 80 % of the territory and where 77 % of the total population live, receive only 32 % of national runoff; it is ironic that the area with the most water constraints in Mexico is also where the most industrial and economic development is present (85 % of the GDP) (Carabias et al. 2005). In Mexico there exist 653 aquifers, which receive a yearly natural recharge and induced recharge of 81.7 km^3, and the average water extraction (in the aquifers) is 31 km^3 although, from a general perspective it seems that the state of the aquifers should be good, the real situation is different. By 2008 the National Water Council (CONAGUA) detected 101 aquifers with overexploitation, 63 of which are in the northern region of Mexico (CONAGUA 2010). In 2010 the coverage of the domestic water supply in Mexico was 91.5 % whereas the connectivity of houses to the drainage system was 90.3 % (INEGI). Even though there was a big improvement compared to 2002, where the coverage of potable water service was 89.2 % and of the drainage was 77 % (Carabias et al. 2005), the current situation cannot be considered optimal because around 950,000 inhabitants are still lacking both services. Of all wastewater produced in Mexico (56,15 % is produced by municipal discharges), only 25 % receives some treatment, while the rest is returned back to water bodies (CONAGUA 2009). This situation provokes extreme ecological damage and serious health problems. Three main indicators are used to determine the quality of surface water in Mexico: BOD_5, COD and Total Suspended Solids (TSS). From the results obtained from 1510 monitoring points over the country, it was determined that 41 % of surface water bodies have an excellent quality based on BOD_5. The situation is similar when considering only TSS (53.5 %). However, if COD is considered, only 28.3 % of surface water is considered excellent. On the other hand, 12.5 % of surface water is polluted or extremely polluted based on BOD_5, and 31 % based on COD (Carbaias et al. 2005).

Therefore, because of all these factors mentioned, it is of high importance to start managing national water resources in a sustainable way. Within this context, since the United Nations Conference on Environment and Development that took place in Rio de Janeiro on June 1992, proper management of water as sustainable resource has been recognized. Several agreements have been signed by many nations since then: a Ministerial conference on potable water supply and environmental sanitation, Noordwijk 1994; World Water Forums, Marrakesh, The Hague, Kyoto, Monterrey, Istanbul and Marseille; World Summit for Sustainable Development, Johannesburg 2002, among others (Carabias et al. 2005).

Among the objectives of the mentioned agreements, it is possible to highlight the following in relation to with water management (UN 1998; www.un.org/millenniumgoals/environ.shtml).

Rio Summit (United Nations Conference on Environment and Development, Rio de Janeiro, 1992),

- To endorse a dynamic, recurrent, interactive and multisectoral approach to water resources management, comprising the identification and protection of potential sources of freshwater supply, which considers, all together, technological, socio-economic, environmental and human health elements.
- To include within the framework of national economic development policy a plan for the sustainable and rational utilization, protection, conservation and management of water resources centred on community needs and priorities.

Millennium goals:

- To decrease the proportion of the population without sustainable access to safe drinking water and basic sanitation by 50 % by 2015.

Nowadays, the term ‘sustainable development’ is commonly used, not only by the scientific community, but also in everyday life. The idea of sustainable development (SD) was initially conceived by Barbara Ward in the mid-1970s, where the economic and social purposes of applied sciences were beginning to become focused on environmental problems (Curwell et al. 2005). But it was not until 1987 that a formal definition of SD was coined in the report of the World Commission on Environment and Development (WCED), also known as the Brundtland Commission report. In this report SD is defined as development to “meet the needs of the present without compromising the ability of future generations to meet their own needs” (Rogers et al. 2008). In other words, the present population should be able to have a continuous economic growth (increasing Gross National Product per capita) and at the same time an improvement of the quality of life – reducing poverty, having access to better education, health care and basic services (such as water supply, sanitation, electricity), enough food for proper nutrition, and having better distribution of wealth; and maintaining natural ecological processes, preserving ecosystems, avoiding/decreasing pollution in the environment, having sustainable utilization of natural resources; without affecting future generations to accomplish the same goals. As can be derived from the last definition, SD has three main elements: economic, social and environmental, which are interlinked (Figure 1.1); in theory, if each element represents sustainable development in itself, then SD is reached.

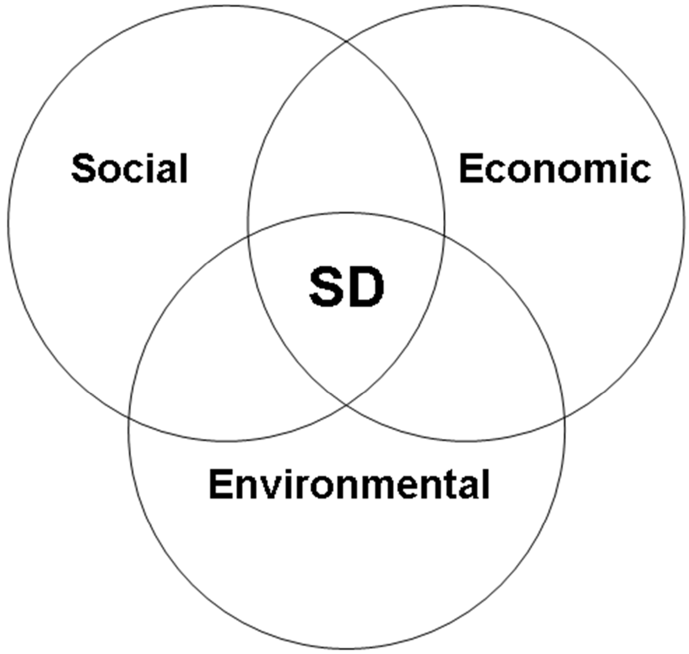

Figure 1.1: The elements of Sustainable Development

But what is sustainability of water as a resource? To answer this question we can look at the definition of the task committee on sustainability criteria, water resources planning and management division of the American Society of Civil Engineers, and the UNESCO/IHP IV Project M-4.3. Sustainable water resource systems are "the systems designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity" (ASCE 1998).

Within an urban context, proper water management systems are designed to provide clean water for different purposes (domestic, public, commercial and industrial uses), to control pollution, to remove and treat wastewater and to prevent storm water and flooding; and to coordinate these actions among local authorities and entities (Hellström et al. 2000; UNESCO 2003). For these purposes these systems should accomplish the following requirements: water quality must be preserved, allowing re-use and recycling of water, not accumulating contaminants (either in surface or groundwater nor in the soil) and improving health and hygiene; extraction of water should not damage the ecosystem and must satisfy the minimum user requirements of quantity and quality, while preserving natural resources, and saving financial resources (Terpstra et al. 1999; Janerette et al. 2006).

To reach a sustainable management system in cities it is important to assess all the technical, environmental, economic and social constraints that directly and indirectly affect the urban hydrological cycle (Hermanowicz et al. 2008). An urban hydrological cycle is composed of seven elements. Firstly, water is extracted from the source (element 1), normally situated in local basins or aquifers, and transported to water treatment plants (element 2) to be purified for reaching the quality standards for human consumption. After treatment, water is distributed through pipelines (element 3) to the final consumer, i.e. domestic, public, commercial or industrial users (element 4). After having been used, water is collected by means of a drainage system (element 5) and is transported to wastewater treatment plants (element 6) in which wastewater is treated in order to reach sufficient quality levels to be returned to local basins or infiltrated back to the aquifers (element 7). In this last step, it is important to mention that the quality of treated wastewater should be enough so as to be further cleaned by natural processes (Gleason et al. 2012).

Based on the urban water cycle, sustainability criteria can be derived: water sources should have enough water available to supply urban agglomerations, satisfying their needs, but without compromising the natural processes of the source (basin or aquifer). Water should be potable and drinkable prior to distribution. The efficiency of the distribution system should be such that most of water extracted is delivered to the final user. Water demand needs to be enough to satisfy the basic survival and hygienic needs of the final user; wastewater must be fully collected and treated while avoiding possibility of infiltration or allocation without previous treatment, and different types of wastewater (domestic, industrial or pluvial sources) should be collected separately. All produced wastewater should be treated with the proper technology according to the specific characteristics of the wastewater. It is important to mention, as was stipulated at the Summit of Rio and the Millennium Goals, that 100 percent of the urban population must have access to clean water and sanitation.

1.1 Megacities and their water constraints

Since the end of the 19th century, the urban population has experienced continuous growth; by 1950, three out of 10 persons worldwide lived in urban areas. Today 50 % of the global population live in cities, and by 2050 seven out of ten will live in urban agglomerations (UN-HABITAT 2012). However, the growth rate of the urban population has decreased over the years and is expected to continue diminishing in the future. In the 1950s, the growth rate of the urban population was 3 %, by the end of the 1980s it was reduced to 2,7 %, currently it is around 1,9 % and by 2030 it is expected to be 1.5 % (reaching 5 billion inhabitants). With these urban growth projections, basically the entire demographic growth of the world will occur in urban areas (UN-HABITAT 2012, Biswas et al. 2006). Since the population started to migrate from rural areas to urban areas at the beginning of the 20th century, many cities started to experience growth (mainly in developing countries like Mexico). In developed countries this growth was gradual (over one century), while in developing countries it was fast, occurring within few decades (after the 1950s and mainly after the 1960s). A clear example of that is Mexico City with a population of 2.9 million in 1950 and 13.4 million in 1980 (Varis et al. 2006; Biswas, et al. 2006).

There exist three different definitions of megacities in the literature; some authors like Varis (Varis et al. 2006) or Jenerette (Jenerette et al. 2006) define a megacity as a city with 5 million inhabitants; on the other hand the UN initially set the limit of a megacity to 8 million, however, due to the fast increase of population in urban centres, this limit was altered to 10 million (Biswas et al. 2006). On one hand, with a definition of 5 million, in 1985 there were 35 megacities in the world, 40 in year 2000, and it is expected that this number will grow up to 58 by the year 2015; on the other hand, if 10 million is taken as the starting point for a megacity, then there were 16 in the year 2000 and there would be 21 by 2015.

More important than setting the minimum population limit for a megacity is to know the constraints that current megacities have, especially those related to water, in order to identify the problems that emerging megacities will have to deal with in the future. Megacities face several challenges such as population growth, mobility, security, poverty, air, water and land pollution, supply of goods, and water supply among others (Kraas et al. 2007). Assuring water supply is one of the biggest problems in megacities. Cities like Mexico City or Istanbul receive a part of their water supply from sources far away from the city. In the case of Mexico City 30 % of the water supplied comes from the Lerma-Balsas and Cutzamala river systems, comprising sixteen dams that have a total storage capacity of more than 2,800 km^3, a primary network with more than 1,000 km and a secondary network with more than 12,000 km (Tortajada et al. 2008). Megacities have become an important focus in terms of water provision, sanitation services and the related impact of urban development on natural resources. The uncontrolled growth of these cities has made water provision and sanitation services to the entire population a difficult, almost impossible, task. This situation gets worse in developing countries where large sectors of the population do not have access to drinkable water and sanitation. Water loss in distribution systems is 30 to 40 percent in megacities. (Tortajada et al. 2008). Another big issue megacities face regarding water management is the management of residual water. As the population of a city increases, more water is consumed and therefore more wastewater is produced. However, just as small percentage of the wastewater produced is treated, as can be seen in cases such as Sao Paulo, Dhaka or Mexico City, producing high levels of water pollution (Varis et al. 2006). Non-revenue waters are a clear representation of the condition and efficiency of the water supply system. In developing countries, due to high public debts, inefficient resource allocation, poor governance, lack of investment capital and inadequate management capacities the necessary infrastructures were not always built on time, and the existing facilities could not be properly maintained (Varis et al. 2006; Saier et al. 2008). As an example, water loss in the distribution system in Mexico City is about 30 %.

The city of Guadalajara, currently with more than 4 million inhabitants and expected to exceed 5 million by 2030, is considered as an emerging megacity. Based on the many water related constrains Guadalajara has suffered in the past, and several bad decisions in domestic water supply management, Guadalajara is currently not considered a sustainable city regarding its domestic water supply. This brings up the question of whether it is possible that Guadalajara will reach the objective of sustainability.

1.2 Research relevance and objectives

In 2000, 13.9 % of the global population was living in cities between one and 10 million inhabitants. By the year 2015, this percentage will increase to 17 %. The main problem in emerging megacities is the lack of appropriate management, adequate institutions and sustainable planning to address the challenges that megacities are presently facing, beyond short-term approaches. Therefore it is considered of utmost importance to evaluate the capacities of emerging megacities to cope with these challenges. As water supply is a necessary aspect of urban development, the design of a tool for evaluating the development of this resource is gaining more relevance. To date, water supply companies (public and private) and city councils evaluate domestic water consumption by dividing the amount of water extracted by the population served. However, there are several aspects involving water consumption that should be considered when evaluating water sustainability. The development of an index that comprises water supply and sustainability can be an important tool to decision makers in order to design and support public policies in water management. This will also provide the opportunity to civic society to monitor the behaviour of the water supply companies and to negotiate with local governments the improvement of water supply management. Another advantage of such an index will be the possibility to benchmark water supply companies in order to adopt best practices. That can only be achieved if the index is not created just for analysing a specific case but also for several different cases.

However, is it possible to measure the sustainability of the development of water supply systems at a local scale by means of a single number? There are several indices to measure sustainable development at the country or regional scale; yet the difficulties of constructing such indices which arise when the scale is reduced might be different. Which will be the best aggregation method which fits with the elements that will describe the sustainability of urban domestic water supply in order to obtain meaningful results?

The main goal of this research is to create a model for evaluating the level of sustainable development of water supply in the metropolitan zone of Guadalajara (MZG), in order to determine if Guadalajara is currently sustainable or not in its domestic water supply. The model will be based on a composite index formed by several indicators which describe the sustainable development of domestic water supply in urban areas. The index should be easy to handle and to understand by decision makers. Furthermore, it should be able to be used in other case studies for comparability reasons.

After determining the level of sustainability Guadalajara currently has, the indicators will be analysed individually to determine the reasons why Guadalajara is or is not sustainable in its domestic water supply. Finally, it will be important to determine if Guadalajara would still be sustainable in the future, in case it is today, or if it would reach a sustainable level, in case it is not.

1.3 Thesis content

The thesis is composed of five chapters. In chapter one, a general introduction to problems of sustainable development is given, together with a description of the sustainable development of water resources. This is followed by a characterization of megacities and their water management constraints. This will help the reader to get an overview of the context of the research, and to understand the ideas presented in this thesis. Also the main objectives of this study are explicated in this chapter. In chapter two, a detailed explanation of the theoretical framework behind the composite indices is given. The different methods to normalize, weight and aggregate indicators into composite indices will be discussed, developing specific rules for selecting the best one, and discussing the advantages and disadvantages of each. This chapter provides the backdrop against which the specific model under use will be introduced, i.e. the water sustainability index (WSI). In chapter three, the model for constructing the WSI is presented, defining the indicators which describe the sustainability of domestic water supply in Guadalajara. Moreover, each indicator is described in detail together with the normalization methods used for each. This chapter gives the reader the opportunity to understand the reasons for selecting the indicators used in the model. In chapter four, a description of the City of Guadalajara and Lake Chapala are presented. This lake, located approximately 40 miles southeast of the city centre, serves as the main reservoir of the urban water supply. The interaction between the city and the lake is explained together with a description of the hydrological cycle of the city. Also a brief summary of the water management history of Guadalajara, the actual water management system of the city, and the legal framework of water management in Mexico are given. Moreover, a detailed description of the results obtained will be presented, which includes the evaluation results regarding the level of sustainability of Guadalajara, a comparison of calculating the WSI using two different aggregation methods, and a detailed description of the results obtained by making use of each indicator. Also in this chapter, the question of generalizability and transferability of the index will be discussed. For this purpose, a comparison between Guadalajara and a supposedly sustainable city (the German capital Berlin) is performed. At the end of this chapter, a prognosis of future local sustainability, based on some of the indicators, will be performed in order to generate three future scenarios of the city of Guadalajara. In the fifth and final chapter, the conclusions of this study are drawn, showing how the objectives of the research were accomplished, and answering the research questions outlined at the beginning. Additionally, hints for future research will be presented. Without anticipating the results too much, it is suggested here to think about future comparisons between several cities in order to determine typical correlations between indicators which could explain increases or decreases in the sustainability of the domestic water supply. The possibility of studying sustainability by using novel methods for constructing composite indices will be discussed in detail, including reflections on the use of additional distribution elements for calculating process capability analysis in non-normal distributions.

2. Theoretical framework: The use of composite indices to measure sustainability

2.1 Definition of composite indices

The complex interaction of all elements which describe a sustainable urban water resource system makes it difficult to get a general or a more detailed picture of the water resource condition, which is not easy to understand by decision makers, and complicates the ability to identify the factors that are affecting sustainability (Gomez Jauregui et al. 2010).

In order to evaluate a phenomenon composed of several elements, it is necessary to use a tool which can condense a large amount of information. A composite index (CI) is a holistic tool that gives the opportunity to aggregate all the elements that describe SD into a non-dimensional number, giving a global overview of the state of the case study (country, region or city). The use of indices as policy tools started in the 1920s, but it was not until the 1990s, right after the summit in Rio, that they began to be widely used in order to evaluate environmental sustainability (Guimarães et al. 2007; Sullivan et al. 2002).

Using composite indices in environmental sustainability assessment offers decision makers the transmission of summarized technical information, keeping the original meaning of the data used for performance monitoring, policy progress evaluation, benchmarking comparisons, and decision making; quantifying a multidimensional phenomenon which cannot be measured directly (Guimarães et al. 2007; Esty et al. 2005; Sullivan et al. 2002).

There exist many composite indices in the literature for sustainability assessment. Each of these indices has specific characteristics and many are the differences among them. Table 2.1 presents an overview of the most referenced indices. However, it is not the aim of this chapter to explain these indices in detail but to present the proper characteristics of a well-designed index, presenting the different options according to the type of indicators that are being used and exposing the different weighting options which are commonly used. For a detailed critique and comparison of indices mentioned in table 2.1, please refer to Appendix II.

Table 2.1: Indices used for sustainability assessment: an overview

Index	Normalization	Aggregation	Reference
Environmental Sustainability Index	**Standardization**	**Arithmetic Mean**	**Esty et al. 2005**
Environmental Performance Index	**Max-Min method**	**Weighted Arithmetic Mean**	**Emerson et al. 2010**
Water Poverty Index	**Standardization**	**Weighted Arithmetic Mean**	**Sullivan et al. 2003**
Ecological Footprint	**Use Ratio Calculation**	**Arithmetic Mean**	**Böhringer et al. 2007**
Environmental Vulnerability Index	**Indicator Grading**	**Arithmetic Mean**	**Böhringer et al. 2007**

There are several pros and cons of using composite indices for environmental assessment (Nardo et al. 2008).

Pros:

- CIs are able to abridge complex, multidimensional information for supporting decision making processes, allowing users to compare complex dimensions tellingly.
- CIs provide a better interpretation rather than several separate indicators.
- CIs permit evaluation of performance of countries over time.
- CIs reduce the number of indicators without losing the essential information base.
- CIs make communication/information to the general public better.

Cons:

- CIs may send confusing policy messages if misinterpreted or poorly constructed.
- CIs may lead to simplistic policy conclusions.
- CIs may be misemployed to endorse a specific policy if the development of the index is not transparent and lacking statistical and conceptual principles.
- The selection of indicators and weights may be subjective.
- CIs may lead to inadequate policies if the performance of indicators is difficult to measure or ignored.

The use of composite indices to evaluate the sustainability of an environmental resource (in this case, water) can be a powerful tool for the decision makers, which can help them to define the best strategy towards accomplishing a sustainable management of the resource. However, one weakness of composite indices is that data can be manipulated to show a better performance than exists in reality or to bias the final result in order to support a determined strategic plan. For this reason, the developers of composite indices must use information only from verified sources and analyse the information statistically, avoiding any possibility of manipulation of data that may change the final result of the index.

2.2 Steps of building a composite index

Figure 2.1 displays how information is condensed until it is presented in the final index. The indicators which compose the index are based on raw data obtained by different means, for example from laboratory analysis, surveys, measurement devices, etc. The information, after being analysed statistically, is grouped into headline indicators (which evaluate the same aspect, such as environmental impact, poverty, and management, among others). Then, the indicators are normalized and a weight is assigned to them accordingly based on their relevance. Finally the headline indicators are aggregated into a single index.

There are four main steps to build composite indices (Nardo, et al. 2008; Hajkowicz, et al. 2006):

- Selection of the proper indicators.
- Normalization of the indicators.
- Weighting.
- Aggregation of the indicators.

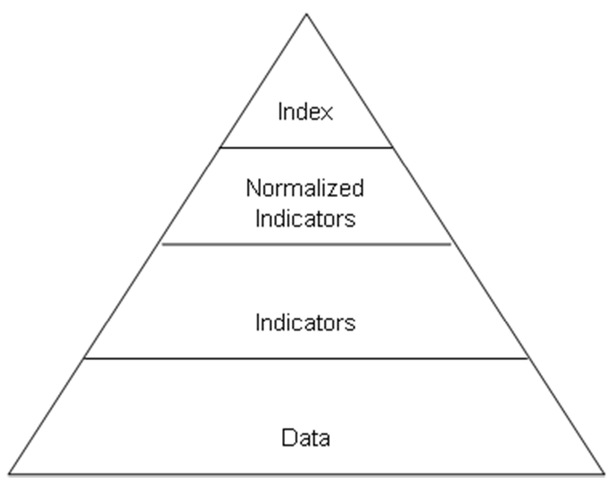

Figure 2.1: The information pyramid (Seljak et al. 2001)

2.2.1 Selection of proper indicators

The selection of indicators is the most important part of building an index; proper selection of indicators will allow the performance of the case to be studied to be described in a reliable way. In the specific case of SD, indicators should be sufficiently comprehensive to capture the multidimensional nature of sustainable development but without being too numerous to have unwieldy results that are difficult to interpret (United Nations 2007).

In order to select the proper indicators for measuring the performance of SD, several characteristics must be considered. Based on these characteristics, it was determined that indicators shall be (Morse et al. 2004; Chaves et al. 2006; Lundin et al. 2003; Niemeijer et al. 2008; De Carvalho et al. 2009; Hajkowicz et al. 2006):

- Available – enough data to describe the behaviour of the indicator and to perform proper statistical analysis (in case necessary) should be accessible.
- Measurable – indicator should be able to be measurable, whether is quantitative or qualitative (in case of scores or ranks).
- Relevant – must be related directly or indirectly to the sought outcomes.
- Understandable – the outcome of each indicator should be easy to understand by several target groups (decision makers, scientists, general public, etc.) and avoid ambiguity.
- Sensitive – the indicator should be able to change as the circumstances involving it also change (global warming, management, economic crisis, etc.).
- Credible – indicators need to be supported by valid and reliable information, and interpreted in a scientifically defensible way.
- Integrative – indicators should be able to interconnect among the aspects of SD.
- Avoiding redundancy – Two or more of the selected indicators should not measure the same characteristic; for example, in water quality, faecal coliform bacteria and E-coli both measure the presence of faecal matter in water, therefore only one should be used.

2.2.2 Normalization of the indicators

Because the indicators that describe sustainable development do not always have the same dimension (Kg, mg/l, USD, etc) it is necessary, prior to aggregating them into a headline indicator or a single index, to convert them into dimensionless unit indicators in order to avoid incommensurability. This process is called normalization (de Carvalho et al. 2009; Sullivan, et al. 2002; Welsch et al. 2005; Esty et al. 2005).

In the literature several methods for normalizing variables are mentioned. Here, the most commonly used ones will be discussed.

- Standardization: By subtracting the mean (μ_i) of the indicator from the observation and then dividing by the standard deviation of the indicator to the value (σ_i), indicators are converted into a common scale with mean zero and standard deviation of one, as described by equation 2.1 (Welsch et al. 2005; Nardo et al. 2008; Blanc, et al. 2008).

$$I(X_i) = \frac{X_i - \mu_i}{\sigma_i} \tag{2.1}$$

  Where $I(X_i)$ is the normal probability distribution of data X_i.

- Linear transformation: There are two kinds of linear transformation; the so called Max-Min transformation is the most widely used in the literature,. Here the observation is compared between the maximum and minimum value among all observations; in case the minimum observation is 0, then the observed value is compared only against the maximum observation (equation 2.2). Here it is important to note that after normalization the maximum observation has a value of 1 and the minimum observation has a value of 0. This transformation method has the advantage of being simple to use; nevertheless, it is influenced by outliers affecting the comparison over time if the maximum/minimum values change (Blanc et al. 2008; Hajkowicz et al. 2006; Juwana et al. 2012; Munda et al. 2005; Nardo et al. 2008; Welsch et al 2005).

$$I(X_i) = \begin{cases} \frac{(X_i - X_{min})}{(X_{max} - X_{min})}, & if\ X_{min} > 0 \\ \frac{X_i}{X_{max}}, & if\ X_{min} = 0 \end{cases} \tag{2.2}$$

  Where $I(X_i)$ is the normalized value, X_i is the value to be normalized, X_{max} is the maximum observed value and X_{min} is minimum observed value.

- Ranking: Defined as the simplest normalization method, here the values of a particular indicator are compared by arranging them in ascending or descending order (equation 2.3). The advantages of this method are its simplicity and that is not affected by outliers; however, performance evaluation and comparisons in absolute terms cannot be achieved (Juwana et al. 2012; Nardo et al. 2008).

$$I(X_i) = Rank(X_i) \tag{2.3}$$

Where $I(X_i)$ is the normalized value and X_i is the value to be normalized.

- Distance to a reference: This method measures the relative position of the indicator with a fixed value used as a reference; this value could be a target, a guideline, an external benchmark case or the average of external benchmarking cases (Juwana et al. 2012; Nardo et al. 2008). The advantages of this method are its simplicity and the fact that it is not influenced by outliers in the case of using a target or a guideline as reference value; nevertheless, when an external benchmarking case (or the averages of the benchmarking cases) is used as reference value, a change in the value of the outliers will modify the final result. The equation 2.4 expresses how this transformation is performed; it is important to note that if the value to be normalized is equal to or higher than the reference value, the normalized value should be 1.

$$I(X_i) = \begin{cases} \frac{X_i}{X_T}, & if\ X_i < X_T \\ 1, & if\ X_i \geq X_T \end{cases} \tag{2.4}$$

Where $I(X_i)$ is the normalized value, X_i is the value to be normalized and X_T is the reference value.

- Categorical scale: A numerical or qualitative category (score) is assigned to each indicator based on defined criteria. Categories can include a numbering from 1 to 5, from very bad to very good or assigned according the percentiles of the distribution of the indicator across all cases. Equation 2.5 describes how this method is used (Juwana et al. 2012; Nardo et al. 2008).

$$I(X_i) = \begin{cases} Y_1, & if\ X_i\ meets\ criteria\ 1 \\ Y_2, & if\ X_i\ meets\ criteria\ 2 \\ \cdots & \cdots \\ Y_n, & if\ X_i\ meets\ criteria\ n \end{cases} \tag{2.5}$$

Where $I(X_i)$ is the normalized value, X_i is the value to be normalized and Y_n is the respective n criteria.

- Annual differences over consecutive years: In this method, the performance of the indicator to be normalized is compared with the performance from the previous year (Nardo et al. 2008). The disadvantage of using this transformation method is that comparisons over different cases cannot be done, only one specific case over time. Equation 2.6 expresses how to perform this transformation.

$$I(X_i) = \frac{X_{i_t} - X_{i_{t-1}}}{X_{i_{t-1}}} \tag{2.6}$$

2.2.3 Weighting

The indicators which describe systems influenced by social, economic and environmental driving forces do not have the same impact on the system. For that reason they should not have the same relevance at the moment of describing the system. For example, in water quality for domestic consumption, the concentration of dissolved oxygen in water has no direct impact on human health; however, presence of pesticides or heavy metals in water does. With this small example it is clear that it is necessary to apply a different weight to each indicator according to its importance (Gomez-Jauregui et al. 2010).

Basically there are three kinds of weighting methods: equal weighting, weights obtained by statistical analysis, and weights based on a participatory approach (Blanc et al. 2008; Paracchini et al. 2008). The selection of the proper weighting method depends on the characteristic of the model to be used, data availability and indicators correlation. It is important to note that normally one rule is applied in all weighting methods. The sum of all weights must be equal to 1 or in other words $\sum_{i=1}^{n}|w_i| = 1$ (Hajkowicz et al. 2006).

- Equal weighting. This is the easiest method for determining the indicators' weights; basically it is based on the assumption that all indicators used in the model have the same relevance, therefore they must have the same weights. This method is used when there is not enough information to determine which indicators are more important than another (equation 2.7).

$$w_1 = w_2 = \cdots = w_n \tag{2.7}$$

  The main advantage of this method is that no further analysis is required to determine which indicator is more relevant than the others, allowing an easy comparison between several countries independent from their characteristics (Esty et al. 2005); however, as it was explained before, not all indicators have the same relevance in real life, so some important indicators maybe eclipsed by others which are not so significant.

- Weighting based on statistical analysis. Statistical analysis such as Principle Component Analysis (PCA) and Factor Analysis (FA) is commonly used in the literature for determining weights. For using PCA and FA, the indicators must have the same unit of measurement. The aim of these two tools is to determine which indicators can describe the most variation in the indicators set; for that reason, the indicators should have a certain correlation level in relation to each other (Nardo et al. 2008). The indicators with higher weights are the ones with a high loading factor, and high percentage in describing the overall variance. In the case that no correlation exists between the indicators, then the weights are considered equal (Juwana et al. 2012). Uses of PCA and FA for determining weights have the advantage that the weights are neutral and solely data dependent. On the other hand, statistically determined weights do not always reflect the priorities of decision makers or budget constraints (Esty et al. 2005).

- Participatory approach. Methods based on the participatory approach, as is stated in the name, are based on opinions, either from experts or general public. The Delphi method, Analytical Hierarchical Process (AHP) and Budget Allocation are examples of these methods (Juwana et al. 2012; Lee, et al. 2007; Nardo et al. 2008). In the Delphi method experts are requested, based on their expertise, to assign a specific weight to each indicator, and give their reasons why they assigned each weight. Afterwards, all reasons given by the experts are summarized, and the experts are requested to answer the questionnaire again after reading the summary of the reasons given. The aim of this methodology is to reach a consensus based on the opinions of the experts, and with this information to be able to determine the weights for each variable (Landeta et al. 2005; Riggs et al. 1983; Schmidt et al. 1997).

  The AHP structures a multidimensional problem into a hierarchical structure assuring that qualitative and quantitative elements are incorporated in the evaluation process. In this method, experts are asked to compare the indicators in pairs indicating which indicator is more important and by how much; the strength of preference is expressed on a semantic scale (from 1 to 9, for example; where 1 represents equality, and 9 represents that indicator A is 9 times more important than indicator B to which it is compared). The pairwise comparisons result in a comparison N x N matrix A, where $A_{ii} = 1$, and $A_{ij} = 1/A_{ji}$. After this, the relative weights of the indicators are calculated using an eigen vector, making it possible to resolve inconsistencies (Kranjc et al.2005; Nardo et al. 2008; Paracchini et al. 2008).

In the Budget Allocation Process, experts are asked to allocate a "budget" of 100 points over all indicators according to their importance, based on their expertise. Weights are calculated using the average of the budgets of each indicator. When this method is chosen for determining the weights, it is important to carefully select the group of experts; giving preference to those being specialists in an evaluation area and not in a specific indicator. The main advantage of this method is that is simple, transparent and of short duration; however, is suitable only for a maximum of 10 indicators to avoid inconsistencies that may be produced when the experts are requested to allocate the budget to a large number of indicators (Nardo et al. 2008).

The problem with statistically based methods and participatory approach methods is that they are not suitable for making international comparisons (i.e. between several countries). In the case of statistical methods, indicators could have different correlations depending on the variation of the individual performance of indicators between nations. For example, GDP per capita could be strongly correlated with water availability in one country, but have a weak correlation in another country; therefore, at the end the weights will be different. In the case of participatory approaches, the judgment of the experts or public opinion in a developing country can be different from those that experts in developed countries give. In this case, experts in Somalia may attribute more relevance to water availability indicators, while experts in Germany may state that environmental impact is more relevant. Therefore it is important to find a weighting method which differentiates the importance between indicators but makes it possible that it be used in an internationally comparison framework.

2.2.4 Aggregation methods into a composite index

The last step of building a composite index is to aggregate all the normalized indicators into a single dimensionless number. In order to do this, several aggregation methods exist. The choice of the proper aggregation method will depend on the characteristics of indicators chosen, the goal of the composite indicator and the nature of the case study (Esty et al. 2005).

The functions describing aggregation methods mentioned in the literature can be divided in three groups, additive, multiplicative and ranking functions. Among the additive functions are the linear sum, the arithmetic mean, the weighted arithmetic mean and the harmonic mean. Under the multiplicative functions, the geometric mean and the weighted geometric mean can be found. The minimum and the maximum functions and multi-criteria approaches are among the ranking methods (Kang et al. 2002; Nardo et al. 2008; Swamee et al. 2000; Zhou et al 2005).

The most widely used aggregation methods for integrating sustainability indicators into a composite index are the additive methods, followed by the multiplicative methods. However, the use of these methods each has different advantages and disadvantages, and certain rules must be taken into consideration at the moment of choosing which aggregation method to use.

- Additive methods. The arithmetic mean and weighted arithmetic mean are the preferred methods used by decision makers. A big percentage of the indices for evaluating either sustainability or water quality consulted in the literature use one of these two methods, and the reason is because they are easy to use and understand. Equations 2.8 and 2.9 describe the arithmetic mean and weighted arithmetic mean respectively.

$$CI(I_i) = \frac{1}{n}\sum_{i=1}^{n} I_i \tag{2.8}$$

Where CI is the composite index, I_i is the i_{th} normalized indicator and n the number of indicators used in the index.

$$CI(I_i) = \sum_{i=n}^{n} w_i\, I_i \tag{2.9}$$

Where CI is the composite index, w_i is the respective weight for indicator I_i, I_i is the i_{th} normalized indicator and n the number of indicators used in the index.

- Multiplicative methods. Similarly to the arithmetic and weighted arithmetic means, the geometric mean and the weighted geometric mean are the most used multiplicative methods, mainly in elaborating water quality indices. Equations 2.10 and 2.11 describe both methods respectively.

$$CI(I_i) = \left(\prod_{i=1}^{n} I_i\right)^{\frac{1}{n}} \tag{2.10}$$

Where CI is the composite index, I_i is the i_{th} normalized indicator and n the number of indicators used in the index.

$$CI(I_i) = \prod_{i=1}^{n} I_i^{w_i} \quad (2.11)$$

Where *CI* is the composite index, w_i is the respective weight for indicator I_i, I_i is the i_{th} normalized indicator and *n* the number of indicators used in the index.

The first rule for selecting the most suitable aggregation method is that the composite index should be meaningful (Ebert et al. 2004). In other words, the ordering of the composite index using non-transformed variables must remain invariant if the same index is built with the transformed variables (equation 2.12).

$$CI(X^1) \geq CI(X^2) \leftrightarrow CI(\phi(X^1)) \geq CI(\phi(X^2)) \quad (2.12)$$

Where X^1 and X^2 are the set of non-transformed data in time 1 and 2 respectively, and $\Phi(X^1)$ and $\Phi(X^2)$ are the transformed set of data by a function Φ on time 1 and 2.

Based on their analysis, Ebert and Welsch defined feasible aggregation methods according the measurement scale of the variables and the desired properties of the index (Ebert et al. 2004; Böhringer, et al. 2007).

There are two types of measurement scales; interval scales and ratio scales (Ebert et al. 2004).From theses, three interval scale functions can be derived: Interval scale non-comparability or INC ($f_i(X_i) = \alpha_i X_i + \beta_i,\ \ \alpha_i > 0$), interval scale unit comparability or IUC ($f_i(X_i) = \alpha X_i + \beta_i,\ \ \alpha > 0$) and interval scale full comparability or IFC ($f_i(X_i) = \alpha X_i + \beta,\ \ \alpha > 0$). Two ratio scales functions can also be formed: ratio scale non comparability or RNC ($f_i(X_i) = \alpha_i X_i,\ \ \alpha_i > 0$) and ratio scale full comparability or RFC ($f_i(X_i) = \alpha X_i,\ \ \alpha > 0$).

While in the case of indicators with INC functions, the best method is to use dictatorial ordering, in indicators with IUC and IFC functions the weighted arithmetic mean is suggested.

In the case of indicators with RNC functions the proposition is to use the weighted geometric mean, whereas for indicators with RFC functions the most suitable method is a homothetic function.

Another problem related to indices is compensation. Compensation occurs when poor performance in one indicator can be compensated for by good performance in another indicator. As weights (equal or unequal) in arithmetic and geometric means express trade-offs between indicators, this implies a contradiction within the definition of weights (to measure the importance of the associated variables). In the arithmetic mean, compensability is constant (perfect compensation), which generates eclipsing between indicators when a low indicator is not reflected in the final index result, resulting in a underestimation of the sustainability index; therefore, in order to avoid compensability in the arithmetic mean, indicators must be preferentially independent, which is difficult to satisfy in environmental contexts (Kang et al 2002; Nardo et al. 2008; Zhou et al. 2005).

On the other hand, the geometric mean is less influenced by compensation because it takes into consideration the differences between the values of the indicators in the aggregation process making it a more appropriate method (Juwana et al. 2012). To show the lesser level of compensation in weighted geometric mean, let us take the next example. Imagine two variables, variable A with weight of 0.71 and constant value over time (from t^1 to t^{10}), and variable B with weight of 0.29 and increasing from one to ten over the same period of time. Then we have three cases: Case I, when A has a constant value of 1; case II, when the constant value of A is 5; and finally, case III with A having a constant value of 10. In the three cases, the variables are aggregated with the weighted arithmetic mean, and with the weighted geometric mean. The results of these indices are presented in figure 2.2.

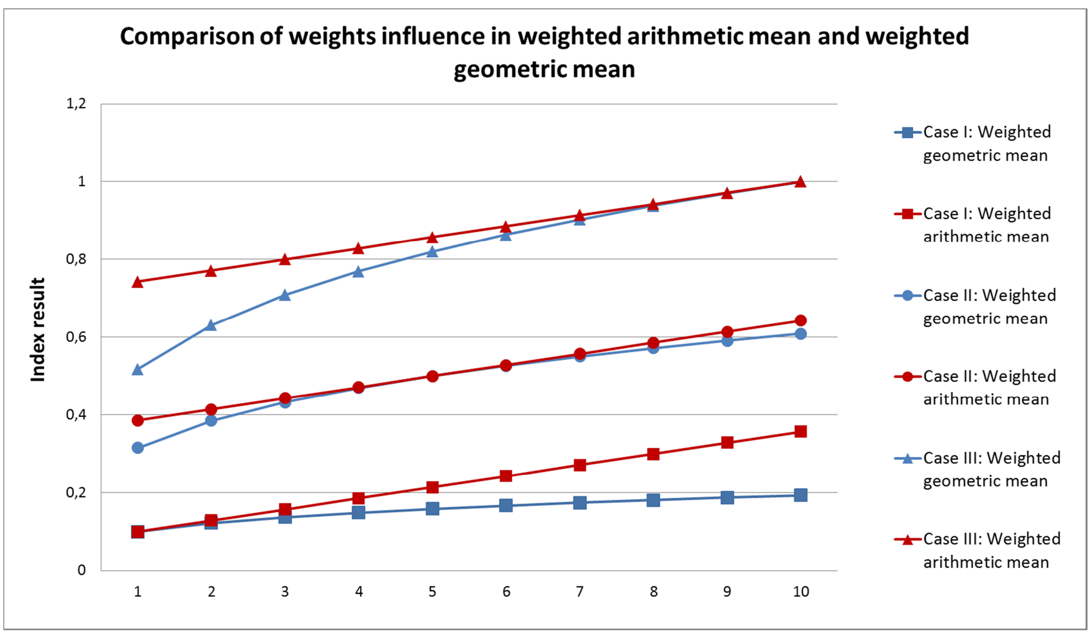

Figure 2.2: Comparison of compensability influence between the weighted arithmetic mean and the weighted geometric mean

Nardo suggests the multi-criteria approach as a good option for aggregating indicators because it is not influenced by compensability; qualitative, interval and ratio scale indicators can be treated jointly, and no normalization of the indicators is needed; however, information on intensity of preference of variables is never utilized, making impossible to know if the ranking between indicators or case studies is due to small or large differences between their individual results, to determine the performance of sustainability of an individual case study over time, or to compare the level of sustainability between several case studies (both main conditions of sustainability indices).

3. Methodology: Water sustainability index (WSI)

The model to describe water sustainability in domestic water distribution in Guadalajara-Mexico will be a weighted composite index using the geometric mean as the aggregation method.

For the model, eleven indicators describing the sustainability characteristics of the domestic water distribution in urban agglomerations are used. Each indicator is normalized (as will be detailed later on this chapter), weights are assigned and then aggregated into a single index.

3.1 Weighted geometric mean as aggregation method

The aggregation method selected was the weighted geometric mean. The reason for selecting this specific approach was to assure the construction of a meaningful index. As was explained before in chapter 2, Welsch determined certain rules to construct unambiguous indices (Ebert et al. 2004). In our case, because all indicators used are non-commeasurable ratio-scale indicators or RNC indicators, the proposed index by Ebert and Welsch is the Cobb-Douglas index (equation 3.1) (Ebert et al. 2004).

$$WSI = \prod_{i=1}^{n} X_i^{w_i} \tag{3.1}$$

Where *WSI* is the water sustainability index X_i, is the i_{th} indicator for measuring water sustainability, and w_i is the corresponding weight for the indicator X_i.

The weighting method used for the WSI was based on a pre-established grading table on which each indicator is graded according to its relation to the water distribution cycle, population well-being and its direct impact in the environment. After each indicator was graded, relative weights were calculated by dividing the grade of each indicator by the sum of all indicators' grades (more details about the weighting method used will be presented in chapter 4).

3.2 Water sustainability index indicators

The indicators used in the index were selected based on a benchmarking process performed by the author using several indicators related to domestic water consumption (Table 3.1). The selection process was done by consulting previous sustainability indices, water sustainability indices and water quality indices existing in the literature. A second selection criteria used was the data availability at a local level; several indices were designed for evaluating countries, therefore it is more likely to obtain the necessary data for all defined variables; this situation changes as the size of the object of study is reduced.

Table 3.1: Water sustainability index indicators

Water sustainability index indicators
Water availability
Water consumption per capita
Water quality
Percentage of population connected to water supply system
Percentage of population connected to drainage system
Gini Index
Percentage of population living in patrimonial poverty
GDP per capita
Water company income/expenses balance
Percentage of water loss in the distribution system vs. total water extracted
Percentage of water treated of total wastewater produced

For all indicators, a detailed description of the indicator, its normalization method and data availability is presented below.

3.2.1 Water availability

Description

A proper definition of water availability is the amount of available water from the sources which can be extracted without affecting the equilibrium of the water body's ecosystem. However, half of the available fresh water supplies are already used in the agricultural, industrial and domestic sectors, and it is expected that this proportion will grow as the demand increases (Jenerette et al. 2006), provoking stress in the environment and breaking its equilibrium.

The case of Guadalajara is characterized by the existence of two main sources of water supply: surface water from Lake Chapala and the Elias Gonzalez Chavez dam, and groundwater from the Atemajác and Toluquilla aquifers. Lake Chapala and the Elias Gonzalez Chavez dam represent 55 % and 5 % respectively of water supply, and ground water represents the other 40 %. Therefore total water availability is calculated by multiplying water availability in Lake Chapala by 0.55, water availability in Elias Gonzalez Chavez dam by 0.05 and groundwater availability by 0.4. Then the total water availability is expressed as:

$$TWA = WA_{Lake}{}^{0,55} * WA_{Aquifers}{}^{0,4} * WA_{Dam}{}^{0,05} \tag{3.2}$$,

where TWA is total water availability, WA_{Lake} is the water availability in Lake Chapala, $WA_{aquifers}$ is the water availability in the Toluquilla and Atemajac aquifers and WA_{Dam} is the water availability in the Ing. Elias Gonzalez Chavez dam.

Normalization

Due to the fact that there are three different water sources that serve as suppliers to the city of Guadalajara, three different standardizations are required (one for each water source) using the Min-Max linear transformation (Nardo et al. 2008). In the case of Lake Chapala, for normalizing this indicator, the maximum value considered for sustainable availability is 4500 Hm^3, which is the natural volume capacity of the lake (CONAGUA 2009A), and 2000 Hm^3 (the minimum permissible volume in Lake Chapala according with "Convenio de coordinación para llevar a cabo el programa sobre la disponibilidad, distribución y usos de las aguas superficiales de propiedad nacional del área geográfica Lerma-Chapala"; Flores, et al. 2009) as the minimum value. Equation (3.3) is used for normalizing this indicator.

$$WA_{Lake_i} = \begin{cases} 0.001, & if \quad Vol_i \leq Vol_{min} \\ \frac{Vol_{sust} - Vol_i}{Vol_{sust} - Vol_{min}}, & if \quad Vol_{min} < Vol_i \leq Vol_{sust} \\ 1, & if \quad Vol_i > Vol_{sust} \end{cases} \tag{3.3}$$

Where WA_{Lakei} is the water availability in Lake Chapala in the evaluation year i, Vol_{sust} is the sustainable water availability threshold in Lake Chapala, and Vol_{min} is the unsustainable water availability threshold in Lake Chapala.

For standardization of water availability in Ing. Elias Gonzalez Chavez dam, the same approach is made as in the standardization of water availability in Lake Chapala. The dam has a maximum storage capacity of 80 cubic hectometres, which is taken as the sustainable volume of the dam. The lowest storage capacity is two cubic hectometres, and will be considered in our model as the unsustainable limit. Equation (3.4) is used for normalizing this indicator.

$$WA_{Dam_i} = \begin{cases} 0.001, & if \quad Vol_i \leq Vol_{Min} \\ \frac{Vol_{Max} - Vol_i}{Vol_{Max} - Vol_{Min}}, & if \quad Vol_{Min} < Vol_i \leq Vol_{Max} \\ 1, & if \quad Vol_i > Vol_{Max} \end{cases} \tag{3.4}$$

Where WA_{dami} is the water availability in the Ing. Elias Gonzalez Chavez dam in evaluation year i, Vol_{max} is the Maximum storage capacity in Ing. Elias Gonzalez Chavez dam, and Vol_{min} is minimum storage registered in the Ing. Elias Gonzalez Chavez dam.

Data availability

For Lake Chapala, monthly information on the lake volume exists from 1939 to 2010. Today the information is updated on a daily basis. For the Ing. Elias Gonzalez Chavez dam, correct information on a monthly basis is available from 2002 to 2009; every year the National Water Commission makes a report of the state of all dams in the basin. As was previously mentioned, there is no information about the state of the two aquifers that supply the ground water; however, according to CONAGUA, both aquifers are presently considered overexploited (CONAGUA 2009B), therefore, a value close to zero (0.001) was assigned to water availability of the aquifers.

3.2.2 Water consumption per capita

Description

The aim of this indicator is to evaluate the consumption per capita in the MZG. The Potable Water and Sewage Intermunicipal System (SIAPA), the public water supply company in Guadalajara, gives service to 79 % of the households in the MZG. The rest of the domestic water consumption is supplied by private wells with concessions given by CONAGUA.

There are two types of water consumption per capita, the first one is the overall consumption (as we have called it) in which the total water consumed (for all purposes) is divided by the number of inhabitants of the city. The second type is referred to as real water consumption per capita, in which only the amount of water supplied for domestic purposes is divided by the number of users supplied; this gives us the real amount of water consumed by the population for domestic purposes. International data sources such as FAO or World Bank present water consumption per capita in terms of total amount of water supplied (for all purposes) divided by the amount of population served. For that reason, it was decided to use the overall water consumption per capita to measure the indicator of "water consumption per capita" of our model.

Normalization

The delimitation values defined for normalizing this indicator are 786 litres which is the maximum consumption per capita in urban agglomerations in 2002 according to FAO (as totally unsustainable), and 160 litres (that is the total amount of daily water per capita consumed in Berlin (taking into consideration all consumption sectors: domestic, industrial, commercial, etc.) as sustainable consumption per capita (Zikos et al. 2008).

In this case, the selected standardization method is the Min-Max linear transformation (Nardo et al. 2008), expressed in the equation (3.5)

$$W_{con_i} = \begin{cases} 1 - \frac{Con_i - Con_{sust}}{Con_{min} - Con_{sust}} & ,if \quad Con_i \geq Con_{sust} \\ 1 & ,if \quad Con_i < Con_{sust} \end{cases} \qquad (3.5)$$

Where W_{coni} is the water consumption per capita in the evaluation year i, Con_{sust} is the sustainable water consumption per capita threshold (in our case the water consumption per capita in Berlin), and Con_{min} is the unsustainable water consumption per capita threshold.

Data availability

This indicator was calculated as the total amount of water billed by SIAPA plus the total amount of water concessions given by CONAGUA in the aquifers of Atemajac and Toluquilla (without considering the concessions given to SIAPA) divided by the total population of the MZG of Guadalajara. The water billing information provided by SIAPA was only for 2007, 2008 and 2009 (no information for previous years was available).

Information about the water extracted from all wells under concessions granted by CONAGUA in the aquifers of Toluquilla and Atemajác is not available. Article 29 Section II of the National Water Law stipulates that all concessionaires must install a water meter or some other water direct or indirect dispositive or procedure to measure water flow, in the first 45 days after the concession was granted. However, after CONAGUA was asked for the data obtained by the water meters installed in all wells under concession, they just provided information about the amount of maximum water extraction each concessionaire can extract per year which is stipulated in each concession.

The data for previous years was built according to the percentage of total distributed water that was actually billed, from 2007 to 2009. The percentage remained practically constant all these years at ~65 % (the average of the percentage of water billed on those years was 65.27 %). Then, the total amount of water distributed from 2000 to 2006 was multiplied by 0.6527 to obtain the total amount of water consumed per year in this period of time. Due to unspecific information about real water extraction in all wells under concession, the information on the maximum amount of water extraction in each concession was used for our calculations, and remained constant in the years of our evaluation period.

3.2.3 Water Quality

Description

Together with water availability, water quality is one of the most important indicators in the model due to the health impacts that this indicator represents.

In water management, it is important to determine if water quality meets the defined standards for the designated use. The supply of safe water to protect human health and well-being is the first concern of water supply companies; therefore, for drinking purposes, water quality indicators should be selected according to their impact on human health (van Leeuwen et al. 2000). In order to have a complete panorama of the quality state of water sources, water quality parameters should be described by physical, chemical and biological characteristics; this full view is necessary for adequate water management. (Ramesh et al. 2010; Boyacioglu et al. 2007; Swamee et al. 2000; Sedeño-Díaz et al. 2007). However, offering decision makers understandable and easy to handle information is becoming a challenging task when water quality variables range from physicochemical to biological variables. The use of composite indices for evaluating water quality permits aggregation of all water quality indicators into a single number that is useful for water managers and easy to understand by the public (Kaurisch et al. 2007; House et al. 1990; Rickwood et al. 2009).

The variables chosen for evaluating water quality were selected based on the available information given by SIAPA and the health impacts defined by the World Health Organization (WHO).

The variables selected for evaluating water quality are showed in table 3.2.

Table 3.2: Water quality variables

Variables	
Ammonia Nitrogen	mg/L
Arsenic	µg/L
Benzene	mg/L
Cadmium	mg/L
Chlorides	mg/L
Dissolved oxygen	mg/L
Faecal coliforms	colonies
Fluorides	mg/L
Lead	mg/L
Mercury	µg/L
Nitrates	mg/L
Nitrites	mg/L
Pesticides	µg/L
pH	
Total dissolved solids	mg/L
Turbidity	NTU

Ammonia nitrogen

The presence of ammonia in the environment is caused by metabolic, agricultural and industrial processes and from disinfection with chloramine. Ammonia is used as surface and ground water quality indicator, because its presence in water may indicate possible bacterial, sewage and animal waste pollution. Although ammonia is not health relevant, it can compromise disinfection efficiency, form nitrite in the distribution system, cause the failure of filters for the removal of manganese and can cause taste and odour problems (WHO 2008). The guideline stipulated by the NOM-127-SSA1-1994 is 50 mg/L; the WHO does not stipulate a guideline for Ammonia nitrogen because its presence in drinking-water is at concentrations well below those at which toxic effects may occur (WHO 2008).

Arsenic

Arsenic is a well known carcinogen; there is overwhelming evidence that chronic consumption of arsenic is causally related to the development of cancer at several sites such as the skin, where it occurs predominantly; but also in lungs, liver, bladder, prostate, kidney and colon. Other health problems provoked by a chronic intake of arsenic are hyper- and hypopigmentation, peripheral neuropathy and peripheral vascular disease (Gray et al. 2008;

WHO 2008). The most important vector of exposure to arsenic is generally through food and drinking water. After the intake, arsenic is absorbed by the blood stream through the gastrointestinal tract, and then is excreted by the urine (WHO 2008).

Higher concentrations of arsenic are present in ground water rather than surface water, due to the presence of arsenic in geological materials; however, high levels of arsenic concentration in surface waters are commonly caused by industrial activities (de Zuane et al. 1997).

The limit stipulated by the Mexican norm NOM-127-SSA1-1994 is 25µg/l; however the guideline suggested by the WHO is 10µg/L.

Benzene

Benzene is one of the most commonly produced chemicals nowadays: just in the United States it ranks in the top 20 chemicals for production volume (Smith et al. 2010). The main sources of benzene in the environment are from petrol and vehicular emissions. Water bodies may be polluted with benzene by industrial effluents and atmospheric pollution (WHO 2008).

Benzene has been proven to be hazardous to humans even at exposure to small concentrations. At high concentrations it is toxic to the central nervous system; and at low concentrations it is toxic to the hematopoietic system causing leukemia, especially acute myelogenic leukemia (WHO 2008; CDC 2007; Smith et al. 2010; Infante et al. 1983).

According with Smith (Smith et al. 2010) there is likely no safe level of exposure to benzene, where hemotoxic effects exist even in exposure levels below 1 ppm. The minimal risk level for oral chronic exposure suggested by the Centre of Disease Control (CDC) is 0.5 µg/kg/day during one year or more (over 90 % of the ingested benzene is absorbed through the gastrointestinal tract). The concentration level in water suggested by WHO is 0.01 mg/L, the same as that suggested by the Mexican norm NOM-127-SSA1-1994 .

Cadmium

Cadmium is naturally more frequently found in ground waters than in surface waters, by its presence in low concentration in rocks, coal and petroleum. Water pollution from cadmium may be caused by mining, industrial activities and leachates from landfills (de Zuane et al. 1997). The main daily exposure to cadmium is via food; and generally, the daily oral intake is 10 to 35 mg. Under cadmium concentrations of 10 µg/L generally no adverse health effects occur. However, in concentrations between 10 and 20 µg/L there could be some adverse health effects. Over 20 µg/L kidney damage has been documented; cadmium accumulates primarily in the kidneys with a biological half-life of 10 to 35 years in humans (Kempster et al. 1997; WHO 2008). The limit stipulated in the Mexican norm NOM-127-SSA1-1994 is 0.005 mg/L.

Chlorides

The presence of chlorine in drinking water is caused by natural sources, sewage and industrial effluents, saline intrusion and, in cities of the northern and southern part of the two hemispheres respectively, due to urban runoff of melted snow containing de-icing salt (WHO 2008).

A presence of excessive chlorine concentrations in the distribution system increases rate of metal corrosion, depending on the alkalinity of the water; increasing the concentration of metals in the supply (WHO 2008). The guideline stipulated by the NOM-127-SSA1-1994 is 250 mg/L; the WHO does not stipulate a guideline for chlorides because the levels found in drinking water are not a health concern.

Dissolved oxygen

Dissolved oxygen in water is the most important element for supporting aquatic life (different species require different amounts of dissolved oxygen to survive), nevertheless is not very soluble in water. The amount of dissolved oxygen in water is inversely correlated with water temperature; when the temperature decreases, dissolved oxygen increases and in high water temperatures dissolved oxygen decreases. However, not only does temperature influence the amount of dissolved oxygen in water, it is also naturally affected by atmospheric pressure, dissolved solids, turbulence and photosynthetic activity of algae and plants. Organic pollutants demand oxygen for their stabilization through biological or chemical oxidation causing depletion of dissolved oxygen concentration (Tebbutt et al. 1998; Jain et al. 2003).

Although the WHO does not have a human-health guideline for dissolved oxygen in drinking water, oxygen-saturated water has a pleasant taste, and water with low dissolved oxygen concentration may indicate presence of pollutants. Therefore, it was decided to include this indicator in the model, taking as a specification limit the limit stipulated by the Mexican Ministry of Environment and Natural Resources (SEMARNAT) which is 4 mg/L.

Faecal coliforms

Several water-borne diseases, including the ones that cause more harm on a global scale, are spread by contamination of water by faecal matter. The pathogens are released into water when faeces of the infected carrier (human or animal) reach the water body; infection occurs when contaminated water with the pathogens is consumed by a person. Cholera, salmonellosis, dysentery are some examples of diseases transmitted by faecal-oral transmission. Some faecal bacteria, like faecal coliform, do not necessarily cause illness but are found in association with some of these pathogens. Therefore, the presence of faecal coliform bacteria in water samples is used as an indicator of faecal contamination of water and the possible presence of these pathogens (WHO 2008; Clark et al. 2000; Tebbutt et al. 1998). For that reason, faecal coliform bacteria is widely used as an important water quality indicator. The Environmental Protection Agency of United States of America (EPA) and NOM-127-SSA1-1994 state as a standard limit for this indicator zero coliform bacteria colonies in the sample.

Fluorides

Fluorine is a common element widely present in the earth's crust in the form of fluorides. Some water bodies present different concentrations of fluorides, and its intake is not harmful in low concentrations. It has been proven that low concentrations of fluorides are beneficial because they have been shown to be inhibitory in tooth decay. However high concentrations of fluorides may cause health problems: Concentrations between 0.9 and 1.2 mg/L may cause mild dental fluorosis, and with the intake of much higher concentrations, 3 to 6 mg/L, particularly with high water consumption, skeletal fluorosis (with adverse changes in bone structure) may be observed (Tebbutt et al. 1998; WHO 2008). Here a difference in the standard limits between EPA and the Mexican Health Ministry is presented; EPA stipulates 2.0 mg/L as the concentration limit of fluorides, while the Mexican Health Ministry stipulates 1.0 mg/L, which is in concordance with the guideline value of the WHO.

Lead

Lead in tap water is more of a result of its presence in household plumbing systems (pipes, solder joints, fitting and/or service connections to homes) rather than natural sources. The lead presented in the plumbing system can be dissolved due to several factors, such as pH, temperature, water hardness and standing time of the water. Lead is an accumulative poison, stored in the skeleton, which produces toxic effects over the years when a continuous exposure is presented. Lead intoxication produces neurological and behavioural effects, mainly in women in their childbearing years, pregnant women, young children and especially bottle-fed babies, at very low concentration. A continuous lead intake produces low intellectual development in children up to 6 years. Also, renal cancer has been linked with high concentration lead exposure (Fertmann et al. 2004; Tebbutt et al. 1998; van Leeuwen et al. 2000; WHO 2008).

The concentration limit of lead suggested by the WHO is 0.01 mg/L which differs from the specification stated in the Mexican norm, 0.025 mg/L.

Mercury

Mercury rarely occurs in a free state, and presents in the form of organic salts and organic compounds. However, synthetic inorganic and organic salts of mercury are widely used in industry (de Zuane et al. 1997). The main natural mercury contamination sources are volcanic eruptions and forest fires associated with clearing agricultural lands; on the other hand, coal-fired power plants and chloralkali plants are the leading point sources of mercury emissions in many industrialized countries (Trasande et al. 2010).

The main source of mercury poisoning for the non-occupational population is food. Elemental and inorganic mercury are released into the atmosphere, elemental mercury is transformed into inorganic mercury, and then the inorganic mercury is deposited in water bodies where it is converted into methylmercury by the action of anaerobic organisms living in aquatic systems. Methylmercury is deposited in the fat of the fish which are later ingested by humans. However, soluble inorganic mercury salts can be found in surface and ground water, usually at concentrations below 0.5 µg/L (WHO 2008; Trasande et al. 2010).

Inorganic mercury produces toxic effects in the kidneys; acute oral poisoning results in haemorrhagic gastritis and colitis, and later on kidney damage. Methylmercury is a strong neurotoxin which affects, mainly, the central nervous system (WHO 2008; Trasande, et al. 2010; de Zuane et al. 1997). The mean daily intake of mercury oscillates between 2 and 20 mg/day. A single dose of 3-30 g, as well daily doses of 75-300 mg/day can be fatal in humans (WHO 2008; de Zuane et al. 1997).

While the guideline formercury suggested by the WHO is 6µg/L for inorganic mercury, the permissible limit stipulated by the Mexican norm NOM-127-SSA1-1994 is 1µg/L.

Nitrates and nitrites

Nitrate is a part of the nitrogen cycle in nature and it is naturally found in soil. Nitrate is also an important nutrient for plants; therefore it is widely used in agriculture as fertilizer. As a consequence of the agricultural use of nitrate, large amounts can reach both surface water and groundwater causing contamination of the water bodies. Other sources of water pollution by nitrates are from wastewater disposal and from oxidation of nitrogenous waste products in human and animal excreta, including septic tanks. Surface water nitrate concentrations can change rapidly owing to surface runoff of fertilizer, uptake by phytoplankton and denitrification by bacteria, but groundwater concentrations generally show relatively slow changes (WHO 2008).

Nitrites in humans are formed by the transformation of nitrates into nitrites by the action of bacteria in the mouth. Around of 25 % of ingested nitrate is recirculated in saliva where 20 % of it is converted into nitrites (WHO 2008).

Nitrate is not harmful for human beings; however, nitrite reacts with the haemoglobin in the red blood cells to form methaemoglobin, which bins oxygen tightly without releasing it, avoiding oxygen transportation. Although most absorbed nitrite is oxidized to nitrate in the blood, residual nitrite can react with haemoglobin. High levels of methaemoglobin (greater than 10 %) formation can give rise to cyanosis; causing health problems mainly in bottle-fed children (WHO 2008). The guidelines stipulated by the WHO are 50 mg/L for nitrates and 3mg/L for nitrites, which are the same stipulated in the NOM-127-SSA1-1994.

Pesticides

Pesticides started to be widely used in the 1950s, with the introduction of newer and more powerful pesticides during the 1960s and 1970s. Pesticides are normally used for pest elimination/control in the agriculture sector, and for vector control in public health (i-e. the control of malaria). There are different classes of pesticides, which include insecticides, fungicides, herbicides and rodenticides, in addition to other substances (Gray et al. 2008; Younes et al. 2000).

Ideally, pesticides are designed to be toxic to specific target organisms; however, that does not occur in reality, where pesticides are also toxic to several non-target organisms, including humans. Therefore; pesticides, which are persistent in the environment and may bio accumulate, are considered particularly hazardous (Younes et al. 2000).

One group of pesticides with a particular applicability to water quality control are the denominated Organochlorine pesticides due their high toxicity, cumulative capacity, slow degradation rate, and persistence in soil after several years of application. There exist several structures of these substances (organochlorine compounds) such as hexachlorocyclohexanes, lindane, chlorinated ethane derivatives like DDT or methoxychlor and cyclodienes – heptachlor (Badach et al. 2000).

Exposure to pesticides causes several health adverse effects. Short-term effects can be mild, as an irritant affecting the skin, lungs, eyes and gut; but also acute effects like a functional and biochemical action in the central and peripheral nervous system are also possible. On the other hand, there is evidence that continuous exposure to pesticides can cause chronic diseases, such as cancer, tumour formation, birth defects, allergies, psychological disturbance and immunological damage (Gray et al. 2008; Younes et al. 2000).

Table 3.3: Permissible concentration limits of pesticides according to the Mexican norm NOM-127-SSA1-1994

Characteristic	NOM-127-SSA1-1994
Pesticides:	µg/L
Aldrin and dieldrin (separated or combinated)	0,03
Chlordane (total isomers)	0,20
DDT (total isomers)	1,00
Gamma-HCH (lindane)	2,00
Hexachlorobenzene	1,00
Heptachlor and heptachlor epoxide	0,03
Methoxychlor	20,00
2,4-Dichlorophenoxyacetic acid	30,00

Table 3.3 presents the pesticides included in the Mexican norm NOM-127-SSA1-1994 with their permissible concentration limits in water for drinking purposes. The permissible limits of the Mexican norm are the same as the guidelines suggested by the WHO; just in the cases of hexaclorobenzene and, heptachlor and heptachlor epoxide, no official guidelines are suggested by the WHO due to the fact the concentrations usually found in water are well below those at which toxic effects are observed.

pH-value

The pH scale indicates the concentration of hydrogen ions present in a substance and is used to measure the intensity of acidity or alkalinity of the substance. The concentration of hydrogen ions is expressed by the function (3.6)

$$pH = Log_{10}\frac{1}{[H^+]} \tag{3.6}$$

resulting in a scale from 0 to 14 with 7 as neutral, below 7 being acid and above 7 being alkaline. Acids and alkalis contained in industrial waste dramatically alter the pH value of the receiving water (Tebbutt et al. 1998; Keller et al. 1992).

Although pH usually has no direct impact on consumers, its control is necessary at all stages of water treatment to ensure disinfection and water clarification; i.e. for effective disinfection with chlorine, the pH should be less than 8; in the other hand, if pH is low, water tends to be corrosive and may damage pipes, and increases the solubility and mobility of trace metals, which can result in the contamination of drinking water, and adverse effects on its taste and appearance (WHO 2008; Jain, et al. 2003). The usual range of acceptable pH in drinking water is from 6.5 to 8; for example, the range stipulated by EPA is 6.5 – 8.5; which is the same range as the Mexican official norm NOM-127-SSA1-1994.

Total dissolved solids

According to the WHO, total dissolved solids (TDS) comprises inorganic salts, such as calcium, sodium, sulphates, chlorides, potassium, magnesium and bicarbonates, among others; and small amounts of organic matter dissolved in water. The origin of TDS in drinking water can be natural or anthropogenic. When TDS has a natural origin, the concentration of salts in water may vary considerably from one geological region to another. TDS affects dissolved oxygen concentration and influences the ability of a water body to assimilate wastes (Jain et al. 2003).

Due to a lack of reliable data on possible health effects associated with the ingestion of TDS in drinking water; the WHO does not propose any guideline for this indicator. However, high levels of TDS in drinking water may produce an unpleasant taste to the customers and also, with time, damage some household items like washing machines, water heaters, etc. The EPA in its 2009 Edition of the Drinking Water Standards and Health Advisories, states 500 milligrams per litre as the maximum TDS allowed in drinking water.

Turbidity

Inadequate filtration or re-suspension of sediment in the distribution system causes presence of particulate matter causing turbidity in drinking water. Turbidity can be caused by clay and silt particles, discharge of sewage or industrial wastes, or by the presence of large numbers of microorganisms such as algae. The presence of turbidity in water affects the efficiency of disinfection; particulates can protect infectious pathogens from the effects of disinfection and can stimulate bacterial growth; turbidity can also inhibit UV disinfection. In water treatment process, turbidity is an important process control parameter, because can indicate problems with treatment processes like coagulation/sedimentation and filtration (WHO 2008).

Turbidity is measured by determining light transmission using standard light sources by nephelometric analysis. The measurement results are expressed in nephelometric turbidity units (NTU) (Keller et al. 1992; Jain et al. 2003). The WHO does not state a health-based guideline for turbidity, nevertheless, for effective disinfection, turbidity should be below 0.1 NTU. EPA and NOM-127-SSA1-1994 set the turbidity limit in drinking water of 5 NTU.

Normalization

Different normalization methods have been discussed in the literature for transforming water quality indicators into a dimensionless unit. The ranging method, used by the Canadian Water Quality Index (CWQI), is one of them. In the ranging method the measured value is compared with the maximum observed value and, sometimes, with the minimum observed value.

Another different approach to normalizing water quality variables is the one used by Bhargava (1983) House (1989), Cude (2001), Liou (2004) and Avvannavar (2008). In this approach, the normalization is based on predetermining rating curves, which describe the relationship between the indicator's result and the normalized value, where a score of 100 represents excellent water quality and a score of 0 represents poor water quality (Rickwood et al. 2009). The rating curves are generated based on specific standards and guidelines, or according with the opinion of experts (House et al. 1989; Kaurish et al. 2007). The use of rating curves for normalizing water quality variables is a subjective approach because is mainly based on the opinion of experts and different guidelines (Kaurish et al. 2007; Boyacioglu et al. 2007; Rickwood et al. 2009). This situation is clearly demonstrated at the moment of comparing the rating curves used by Boyacioglu, Avvannavar, Liou and Cude; all generated curves for the same variables use different functions; for example, pH .

The third method is the one used by the Environmental Sustainability Index (ESI) developed by Yale and Columbia University (Esty et al. 2005); in the ESI, standardization is used to normalize the water quality variables (equation 2.1).

Just some authors mention whether they use the mean of the distribution for normalizing each water quality indicator, or whether they use just a single measurement; Liou (2004), Debels (2005), Bordalo (2006), Boyacioglu(2007) and Sedeño-Díaz (2007) are among them. Using the mean of the data sets for calculating a water quality index has two main failures: the first one is to assume that the distribution has normally distributed behaviour, which occurs in rare cases (because several variables of water quality evaluation are naturally left-bounded by zero); as it will be presented later in this dissertation, the majority of indicators used in this research present positively skewed distributions. The second failure is, assuming the variables follow a normal distribution, that in some instances the mean could show being in accordance with the guidelines; however, a considerable number of values measured are not (something that could occur if the distribution has a negative kurtosis and the distribution mean lies near the guideline value); in other words, a water quality indicator may be considered in acceptance, even if a large number of samples were unacceptable. This example shows how the use of the mean for evaluating a quality behaviour could lead to an incongruity.

In order to avoid the problems previously explained, a different and innovative approach is suggested in this research. Taking the experience of statistical process control (SPC) developed for monitoring production quality in the automotive industry; process capability indices (PCI) were selected as the best methodology to normalize the water quality indicators used in this index. PCIs determine whether a process is capable of producing items in between defined specification limits; giving a dimensionless number which represents the percentage of the distribution inside the specification limits. There are two main PCIs, the Cp and Cpk: "Cp indicates process potential performance by relating the natural process spread with the specification spread; Cpk indicates the process actual performance by accounting for a shift in the mean of the process toward either the upper or lower specification limit" (Suozzi et al. 1999). As is stated by Suozzi, our interest is to determine how the actual performance of our variables' distributions are compared with the permissible limits for drinking water quality (specification limits). Equation 3.7 expresses how to calculate the Cpk.

$$Cpk = \min\left\{\frac{USL-\mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\} \tag{3.7}$$

Where USL is the upper specification limit, LSL is the lower specification limit, μ is the distribution's mean and σ is the distribution's standard deviation.

Originally, the equations used to calculate the PCIs were formulated under the assumption that the evaluated processes follow a normal distribution. It is known that this situation rarely happens in water quality indicators, which have usually positive skewed distributions. Different methods have been discussed in the literature to calculate PCIs for non-normal distributions. Transformation methods applied to the data for converting the non-normal distribution into a normal one and then estimating the PCIs with the classical method, together with the percentile method, are some of the most commonly used in the past (Hosseinifard et al. 2009).

Several transformation functions can be used for transforming data. Among them the logarithmic transformation function, square root transformation and power transformation (Rosas et al. 1995). Table 3.4 shows these functions.

Table 3.4: Transformation functions

Logarithmic transformation.	$X_{Ti} = \ln(X_i)$
Square root transformation	$X_{Ti} = \sqrt{X_i}$
Power transformation	$X_{Ti} = \dfrac{X_i^{\lambda} - 1}{\lambda \dot{X}^{\lambda - 1}}$

Where X_{Ti} is the ith transformed data, X_i the ith original measured data, $\dot{X} = \left(\prod_{i=1}^{n} X_i\right)^{\frac{1}{n}}$ and the exponential variable λ can have values from -1.5 to 1 (Rosas et al. 1995).

The second methodology mentioned is the method developed by Clements. In this method, Clements uses the Pearson family of curves for determining the PCIs in non-normally distributed processes. In his method, Clements uses the median, the 99.865th and the 0.135th and the 50th percentiles for calculating the Cpk (equation 3.8). Then the skewness and kurtosis of the distribution are estimated in order to allow determination of the standardized values of the median, the 99.865th and the 0.135th using the tables of standardized tails of Pearson curves (Clements et al. 1989).

$$Cpk = \min\left\{\frac{USL - M}{(99.865\xi - M)}, \frac{M - LSL}{(M - 0.135\xi)}\right\} \tag{3.8}$$

Where *USL* is the upper specification limit, *LSL* is the lower specification limit, *M* is the median and ξ is the symbol for percentile.

These two methods for determining the Cpk_s in non-normal distributions have some disadvantages. With the transformation methods, if it is possible to transform the non-normal distribution into a normal distribution, then is possible to use the regular functions for determining the PCIs; however, it is difficult to interpret the result obtained because it is necessary to transform it back, which is extremely difficult if not impossible almost all the time. In the case of the Clements' method as well as in the transformation methods, a minimum of 100 measurements for each variable is needed for calculating PCIs (Ding et al. 2004; McCormack et al. 2000; Tang et al. 1999; Wu et al. 2007).

For the physicochemical water quality indicators, like heavy metals or nitrates, the sampling period stipulated in the Mexican norm NOM-179-SSA1-1998 is trimestral; therefore, just a small number of samples are taken in a period of a year. In the case of SIAPA, these indicators are sampled on a monthly basis, so a minimum of 12 samples per year are available for each treatment plant. As was explained before, transformation and Clements' methods need to have at least 100 samples to be used for calculating PCIs. Nevertheless, another methodology for calculating PCIs for non-normal distributions where the sample size does not play an important role was developed by Chang, Choi and Bai; this new method is a heuristic method which uses weighted standard deviations for calculating PCIs (Chang et al. 2002). The method developed by Chang, Choi and Bai starts from the premise that the standard deviation of the quality characteristic X (σ_x) can be divided into upper and lower deviations representing the degree of the dispersion of both sides from the mean μ_x. Based on this statement, an asymmetric distribution can be approximated by two normal distributions with the same mean but different standard deviations (Chang et al. 2002). In this heuristic method the C_{pk} is defined as:

$$C_{pk}^{WSD} = \min\left\{\frac{USL-\mu_x}{6P_x\sigma_x}, \frac{\mu_x - LSL}{6(1-P_x)\sigma_x}\right\} \tag{3.9}$$

Where USL is the upper specification limit, LSL is the lower specification limit, μ_x is the mean of the quality characteristic X, σ_x is the standard deviation of the quality characteristic X and P_x is the probability of X to lower or equal to μ_x. For a finite number of samples, C_{pk} can be estimated by:

$$\hat{C}_{pk}^{WSD} = \min\left\{\frac{USL-\overline{X}}{6\hat{P}_x S_x}, \frac{\overline{X} - LSL}{6(1-\hat{P}_x)S_x}\right\} \tag{3.10}$$

Where X is the sample mean, S_x is the sample standard deviation and P_x is defined as:

$$\hat{P}_x = \frac{1}{n}\sum_{i=1}^{n} I(\overline{X} - X_i) \tag{3.11}$$

where $I(x)=1$ for $x \geq 0$ and $I(x)=0$ for $x<0$.

As a result of the low number of measurements per year for some of the water quality indicators; the fact that the distributions of the water quality indicators present different behaviours over the evaluation period with, sometimes, an skewness larger than 2; and because it is easy to use in the field and to be understood by decision makers; it was decided to use the approach of Chang, Choi and Bai for determining the PCIs of the water quality indicators used in our model.

Also, for some indicators such as lead or mercury, a considerable number of the measurements available are presented in the format of “measurement ≤ guideline,” with which it is not possible to perform a proper statistical analysis. For these indicators, the percentage of measurements which meet the guidelines was calculated, and the result obtained was used in the index.

Data availability

The data used for developing the necessary statistical analysis in order to determine the PCIs were provided by SIAPA from the water treatment plants 1, 3 and wells. The data corresponded to the period of time from January 2000 to December 2009. The samples and sampling period were obtained in accordance with the Mexican norm NOM-179-SSA1-1998: Surveillance and evaluation of water quality control for domestic drinking and usage proposes.

3.2.4 Percentage of population connected to water supply system and percentage of population connected to drainage system

Description

Water accessibility is highly linked with the level of poverty of a community, and access to safe water is necessary for an adequate quality of life (Sullivan et al. 2003). With water being considered a human right, access to water is an important indicator for sustainability of a society. Also, when more of the population have access to improved sources of drinking water supply, the higher the capacity of the city to provide a healthy environment which will result in reducing risks associated with water-borne diseases and exposures to pollutants (Esty et al. 2005).Therefore, measuring water accessibility was included as a key element of measuring sustainability in domestic water consumption.

Wastewater systems should be able to remove wastewater to prevent unhygienic conditions, as well to remove rainwater to avoiding damage from flooding (Hellström et al. 2000). The absence of an inadequate disposal of wastewater represents serious risks for population health and the environment. Outbreaks of faecal and/or urine-borne diseases, such as cholera or hepatitis A, among others, have a high probability of occurring in the absence of a proper wastewater system. Furthermore, freely disposing wastewater directly to the local ecosystem may pollute ground water aquifers located in the area, severely affecting their quality. For these reasons, the number of houses in a city connected to the wastewater system must be considered as one of the indicators for measuring the development of the city.

These two indicators are designed to separately measure the percentage of houses out of the total number of houses in the city of Guadalajara that are connected to the water supply system and to the drainage system.

Normalization

As result of these two indicators being already expressed in terms of percentages, no normalization is needed.

Data availability

The data used for these two indicators were obtained from the Population and Housing Census 1990, 2000 and 2010, and Population and Housing Counting 1995 and 2005. In Mexico, the Census takes place every 10 years at the beginning of each decade. The national count is also performed every 10 years, but in the middle of the decade. More information is collected in the Census than in the Count, but all information requested in the Count is also requested in the Census.

Because results of the censuses previous to 1990 were lost, at a local level, in the earthquake that Mexico City suffered in 1985; it was not possible to use this information to determine the trend in water and drainage connectivity of Guadalajara in the years previous to 1990. Nevertheless, with the information at a state level (Jalisco) obtained from the previous census, a trend was determined by using a regression leading to a logarithmic function that describes better how these indicators behave at a state level. Consequently, a regression using a logarithmic function was performed with the data of 1990, 1995, 2000, 2005 and 2010 for the city of Guadalajara.

3.2.5 Gini Index, Percentage of population living in patrimonial poverty and Gross Domestic Product (GDP) per capita

Description

In several sustainability indices GDP per capita, the percentage of population living below the poverty line or the level of income inequity are used for measuring socio-economic aspects of sustainable development. However, none of them combine the three values listed above in the indices. Atkisson, Han and De Carvalho measure income inequity as a socio-economic indicator; similarly, van Dijk together with Han includes GDP per capita as an economic indicator in their indices; and finally, Lee and van Dijk also evaluate the percentage of population or houses living below the poverty line (Atkisson et al. 2001; Han et al. 2008; De Carvalho et al. 2008; van Dijk et al. 2005; Lee et al. 2007).

Nonetheless, a society can be only considered socio-economically sustainable if has a sustainable economic growth, low poverty level, and income that is equally distributed. The World Bank defines the GDP as: "The value of all final goods and services produced in a country in one year (see also gross national product). GDP can be measured by adding up all of an economy's incomes- wages, interest, profits, and rents- or expenditures- consumption, investment, government purchases, and net exports (exports minus imports). Both results should be the same because one person's expenditure is always another person's income, so the sum of all incomes must equal the sum of all expenditures" (http://www.worldbank.org/depweb/beyond/global/glossary.html). In a few words, the GDP is used to measure the economic performance of a specific entity (country, region, continent, etc.), (Morse et al. 2004). GDP measures just the level of economic growth, but does not take into consideration the level of poverty or whether the wealth represented by the GDP is equally distributed or concentrated in just a few hands.

Therefore, to measure the real socio-economic development of a city, the poverty level and the income equality must also be determined. This situation can be clearly explained with the next hypothetical example: Imagine the case of a country which has continuous economic growth, but the with a large part of the population living below the poverty line; it is clear in this example that the country's wealth is concentrated in just a few; for example, India in 2009 was the eleventh economy in the world in terms of total GDP (World Bank data base), however, 55 % of the population in India are poor (UNDP 2010).

The Gini Index measures the difference between the real distribution of income and the hypothetical distribution in which each person gets the same income. The Gini index can be expressed graphically according figure 3.1; where the Gini index is determined as:

$$Gini = \frac{Area \quad A}{Area \quad (A+B)} \tag{3.12}$$

A Gini index of 0 represents a situation in which the whole population receives the same income, and a Gini index of 1 means that the whole wealth is concentrated in just one member of the population.

Population living in patrimonial poverty is defined as the population with an income per capita that is not enough to satisfy food, health, education, housing and services (Yúnez-Naude et al. 2009). The National Council of Social Development Policies Evaluation (CONEVAL for its acronym in Spanish) defines Patrimonial poverty as: “The insufficiency in the available income to acquire the basic food basket, just as to make the necessary expenses in health, clothing, housing, transportation and education, even though the totality of the income is used exclusively for the acquisition of these goods and services” (CONEVAL 2007).

For evaluating the socio-economic development of the city of Guadalajara, GDP per capita in prices of 2003, the Gini Index of income inequality and the percentage of population living in patrimonial poverty were used as socio-economic indicators.

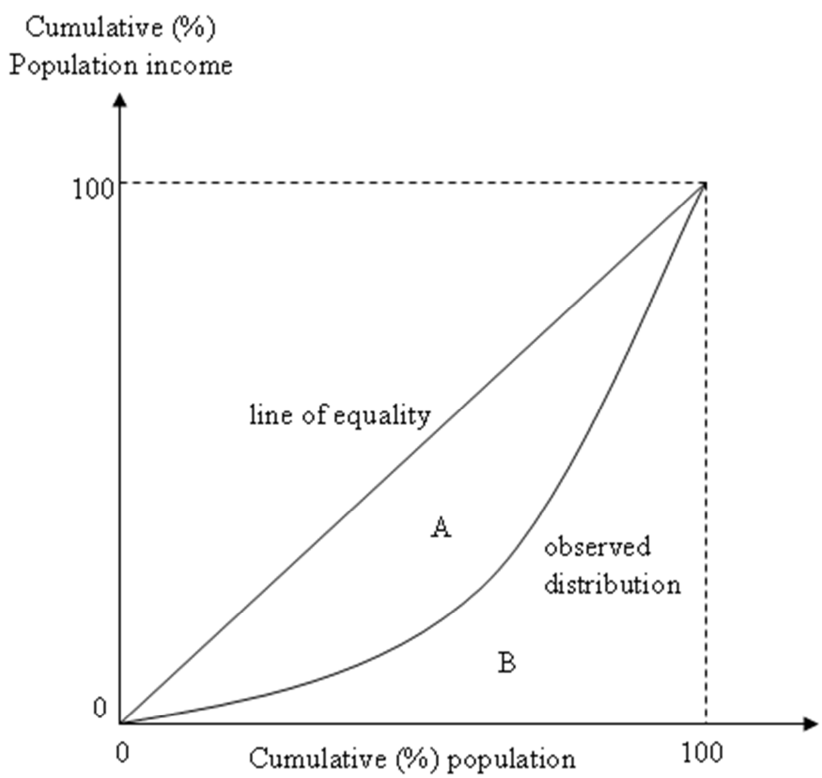

Figure 3.1: Graphical representation of Gini Index (Source: Morse et al. 2004).

Normalization

In the two first indicators no normalization is needed because, patrimonial poverty is already expressed in percentage, and the Gini index is already a one-dimensional number between 0 and 1; however, in both indicators the best performance is represented by a zero and the worst performance by a one. Therefore, in order to be aggregated into the final index, the difference between one and the indicator's result must be calculated and the result of this subtraction is the one to be aggregated.

In the case of GDP per capita, normalization is necessary. Equation 2.2 was selected to normalize this indicator. However, in order to reduce distances between the best practices and the worst practices, it is necessary to perform first a logarithmic transformation of the indicator's result and the maximum and minimum reference values: the maximum and minimum GDP per capita for each year were taken from the World Bank's GDP per capita data using GDP per capita with prices of 2005.

Data availability

The information for calculating the percentage of people living in patrimonial poverty was obtained from the Population Council of the State of Jalisco (COEPO, for its acronym in Spanish). COEPO determined the percentage of people living in patrimonial poverty for all municipalities of the state of Jalisco; I calculate the percentage of people living in patrimonial poverty in the city of Guadalajara, multiplying the percentage obtained by COEPO for each municipality that composes the MZG with the total population of the respective municipality, adding the result and calculating the total percentage of people living in patrimonial poverty in Guadalajara. The data available in COEPO is for the years 2000 and 2005; to determine the poverty level in the rest of the years, a linear function was selected as the best one to model the patrimonial poverty behaviour over the last 10 years in Guadalajara, because of the small change presented between 2000 and 2005; and it is unlikely that poverty in a city will change drastically from one year to another in normal circumstances.

For the case of the Gini Index, the data was obtained from the United Nations Report "State of the World's Cities 2010/2011" (UN-HABITAT 2011) the data presented in this report specifically for Guadalajara are for 1992 and 2005. Also there is a small change in the index from 0.455 to 0.44 respectively; therefore, again a linear function was generated to describe the behaviour of this indicator over the years.

For calculating the GDP of Guadalajara, I used the available GDP information from Jalisco for the years 2003 to 2008. The information was obtained from the System of National Bill of Mexico (http://www.inegi.org.mx/est/contenidos/proyectos/cn/pibe/tabulados.aspx).

Comparing the results of total gross production by sector of Jalisco and Guadalajara in 2004, the contribution of Guadalajara to the GDP of Jalisco in each sector was determined. Assuming the percentage of Guadalajara's contribution to Jalisco's GDP remains constant over the years; the GDP of Guadalajara was calculated. For the previous years (2000-2002) an exponential trend function was generated using the data from 2003 to 2009.

3.2.6 Water company income/expenses balance

Description

A tariff system is the collection of prices, rights or imposed taxes to one or several services provided by an institution or company with the fundamental goal of recovering their capital, financial and operations costs that allows them preserve their patrimony (Tortajada et al. 2004). A water supply company is considered economically sustainable (as are other companies) when its incomes are greater than its expenditures. The water company's income should be enough to recover the inversion, operation and maintenance costs and to invest in the conservation and extension of the infrastructure in order to avoid its deterioration (Tortajada et al. 2004). This indicator is intended to determine whether the water company is financially self-sufficient, measuring the relationship between income and expenses of the company.

In the case of the city of Guadalajara, around 95 % of the water supplied for domestic/public use purposes is supplied by SIAPA, and with SIAPA being a public company, should be available to function properly and to improve its service without the need for subsidies. Evaluating the financial balance of SIAPA can indirectly determine if the company receives governmental subsidies or not.

Normalization

In this indicator the income is presented as a percentage of the expenses. In the case that income is more than the expenses (considering also the money spent in inversions), then the final result will remain as one; otherwise, the result is the percentage of the income vs. the expenses.

Data availability

The necessary information to build this indicator was obtained from the financial balance of SIAPA. The information is available from 2002 to 2010; for the previous years, an exponential regression was performed to determine the missing values.

3.2.7 Percentage of water loss in the distribution system vs. total water extracted

Description

In a distribution system, a part of the water supplied is always lost. This water loss is usually denominated "unaccounted-for water" and can be in a range of eight percent in Singapore to 65 percent of the total water supplied in Damaskus (Zehnder et al. 2003). There are two major causes of water loss: physical reasons such as leakages in the pipes, and commercial reasons like illegal connections or malfunctioning meters (Zehnder et al. 2003). The ideal situation should be to have no water loss during distribution, neither physical nor economical; however, this is almost impossible; nevertheless, reducing leakages to the minimum should be the goal in every water supply system. This indicator evaluates the state of the distribution system by measuring the amount of water loss in the distribution system compared with the total amount of water extracted.

Normalization

As the result of this indicator is expressed in terms of percentage, no normalization is needed and for aggregation purposes the difference between one and the percentage expressed in decimals will be taken.

Data availability

Three possible points for water loss in the water supply network are: between the water extraction and the water treatment plants, inside the distribution network and inside the dwellings. Because it is extremely difficult to measure the amount of water loss from the leakages inside the house, in this indicator just water loss from water extraction to water delivery is considered.

SIAPA does not possess flow or pressure meters to monitor water loss in the distribution network; therefore, in order to be able to calculate water loss it is necessary to subtract from the total amount of water extracted in a specific period of time (in our case, a year) the amount of water delivered to the final consumers. Unfortunately, SIAPA only has information of the amount of water billed from 2007 to 2009; for that reason, the percentage of water billed vs. water treated on those years was calculated resulting in a stable behaviour. As a consequence, the average of these percentages was computed and used to determine the hypothetical water consumption for the period of 2000 to 2006.

3.2.8 Percentage of water treated of total wastewater produced

Description

As a city grows, its water demand also increases. Larger water consumption means a larger wastewater production. A large percentage of released wastewater is not properly treated or not treated at all, polluting water bodies (Zehnder et al. 2003). Treating wastewater in totality before delivering it to the normal hydrologic cycle is critical to reduce environmental and health impacts of the use of water on human activities. At present, in Latin America less than 10 % of the wastewater generated is treated properly and disposed in an environmentally-safe way (Biswas et al. 2006). As a goal for reaching sustainability in water consumption, 100 % of wastewater produced should be treated. In the same way, to reduce water consumption (and therefore reducing wastewater production), treated wastewater can be re-used for different purposes or activities in which using water with high quality is not necessary, such as watering gardens and public parks, or for industrial processes where water quality is not critical.

Normalization

Because the results of this indicator are expressed in percentages, no normalization was needed.

Data availability

Nowadays, SIAPA is the main body responsible for wastewater treatment in the MZG after overtaking the responsibilities from CEA which was fully responsible for the wastewater treatment previously. The information for this indicator was provided by SIAPA. According to SIAPA, wastewater treatment in Guadalajara started in 2002 and the reuse of treated wastewater started in 2005.

4. Water sustainability index for evaluating the city of Guadalajara

4.1 Overview of the area of study

4.1.1 Guadalajara

The city of Guadalajara is the capital city of the state of Jalisco and with an actual population of 4,434,878 inhabitants and an area larger than 550 square kilometres, in 2004, the area of the urban sprawl of the city of Guadalajara was 544.7 square kilometres (figure 4.1) (Aguilar et al. 2004): It is the second biggest city in Mexico and the third most industrialized city after Mexico City and Monterrey. The urbanized zone of Guadalajara is located in 8 municipalities: Guadalajara, Zapopan, Tlaquepaque, Tonala, Tlajomulco de Zuñiga, El Salto, Juanacatlán and Ixtlahuacan de los Membrillos; altogether, the area of the 8 municipalities is 2734 square kilometres. Guadalajara contributes at a level of 70 % to the GDP of Jalisco, which represents 6.6 % of the national GDP. The main economic activities of Guadalajara are commerce, manufacturing and real estate, among others (http://sieg.gob.mx).

The city of Guadalajara is located across the Atemajac valley (between the coordinates 20º 19’ and 20º 54’ latitude north, and the meridians 103º 05’ and 103º 35’ longitude west), at an altitude of 1500 to 1600 m above sea level. It is delimitated to the east by the Santiago River, to the northeast by the Huentitan/Oblatos ravine, to the west by the Primavera Forest and far away to the south by the Viejo and Chupinaya mountains. Guadalajara has a temperate climate, with temperatures ranging between 11 °C and 28 °C (with extreme minimum of -3.5 °C and maximum of 39.6 °C), with a rainy season from the beginning of July to the end of October/beginning of November. The average precipitation is 78.5 mm per year, however, during the rainy season precipitation may reach 390 mm (SMN data from 1981-2000).

The hydrology of Guadalajara is composed of two hydrological basins, Atemajac and Toluquilla. The Atemajac basin is composed of the Atemajac-Tesistan aquifer and by 12 sub-basins of which the Atemajac River and the San Juan de Dios River basins are the most relevant. On the other hand, the Toluquilla basin does not have permanent superficial affluent, only temporal streams which are formed by runoffs during the rainy season. One of these streams is part of the Ahogado sub-basin which includes the Ahogado dam. The main water allocation in Toluquilla basin is the Toluquilla aquifer, which together with Atemajac aquifer are the only two aquifers under Guadalajara.

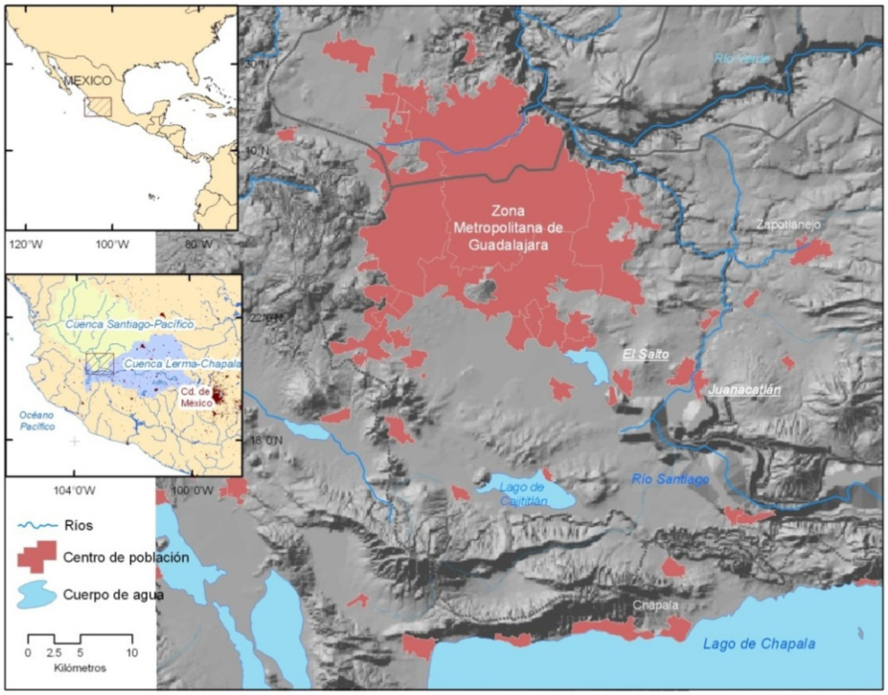

Figure 4.1: The Metropolitan zone of Guadalajara (ITESO 2009)

The main sources of freshwater in the urban zone of Guadalajara are Lake Chapala with 5.5 m^3/sec, Atemajac and Toluquilla aquifers with an extraction rate of 2.57 m^3/sec, the Elias Gonzalez Chavez dam with 1.08 m^3/sec and springs with 0.15 m^3/sec; producing a total supply of 9,3 m^3/sec (considering only water extracted by SIAPA) (SIAPA, August 2008). Lake Chapala is the most important water source for the city of Guadalajara.

In Guadalajara the domestic sector is the main water consumer, using around 70 % of the water supplied: the rest is used by the commercial, industrial and public sectors. SIAPA, which is in charge of supplying 93 % of the total water distributed to the city, is the biggest water management entity; the rest of the water is supplied by each municipality or is water licensed by CONAGUA.

4.1.2 Lake Chapala

Lake Chapala is the largest natural water reservoir in Mexico, the second in altitude in America and the third in size in Latin America. Lake Chapala is located in the western part of the country, between the parallels 20° 07’ and 20° 21’ latitude north and the meridians 102° 40’45” and 103° 25’30” longitude west and at an altitude of 1524 m above sea level. The lake has a surface area of 1146.7 km^2 which is shared between the states of Jalisco and Michoacan in a proportion of 86 % - 14 % respectively (figure 4.2) (Guzman, et al. 2003).

Figure 4.2: Lake Chapala (source www.geo-mexico.com)

The lake has its origins in a fault in the terrestrial cortex, originating from a tectonic trench, which collected water from the Lerma-Santiago hydrologic system. Lake Chapala is a shallow lake with an average depth of 6 meters, and maximum depth of 11 meters, therefore is very susceptible to depth changes (Filonov et al. 2002). The maximum storage capacity of the lake is 9690 hm^3, however this volume was reached for last time in 1934 (van Afferden et al. 2004).

The clime in the zone of the lake is classified as semi-hot sub-humid with seasonal rainfalls during summer. The average annual temperature is 19.9 °C with maximums of 27 to 30 °C from May to July, and minimums of 9 to 12 °C from December to February.

The main water inflow is rain precipitation, with average precipitation inflow per year of 855 hm^3 (with maximums and minimums of 1373 and 340 hm^3 between 1934 and 2001 (CONAGUA 2010 B)), followed by the inflows of the Lerma, Duero and Zula rivers with an average water inflow of 1460 hm^3 per year (data from 1934 to 2001, CONAGUA 2010A) and only 707 hm^3 on average per year from 1990 to 2001; and local run-offs during the rainy season. The main outflow of the lake, due to its shallow waters, is by evaporation, at 1430 hm^3 on average per year, followed by the outflow through the Santiago River/Atequiza canal and water extraction through the Chapala-Guadalajara aqueduct, at 404 hm^3 on average per year (data from 1992 to 2001, the year after Chapala-Guadalajara aqueduct was fully operational).

4.1.3 Urban water management in Mexico

In order to understand how water is administered in Guadalajara it is necessary to look at how water management is structured in Mexico; which dependencies are involved and what their interactions are.

From 1948 to 1983 the planning, development and management of the urban water systems were performed by entities belonging to the federal government; during that period, urban drinking water policies were controlled by the federal government. In 1948, under the mandate of President Miguél Alemán (1946-1952), the ministry of hydric resources (SRH for its acronym in Spanish) was made responsible for the urban drinking water systems in Mexico, through the general director of drinking water and sewage (DGAPA for its acronym in Spanish). This organisation was in charge of planning, programming and managing the urban water infrastructure from 1948 to 1971. In 1971, after the growth of number of hydrological systems in Mexico, SRH created a new director: the general director of drinking water and sewage system operation (DGOSAPA), dedicated to supervising and operating the systems (Pineda et al. 2002).

In 1976, due to the extensive number of urban water systems in Mexico, the responsibilities of SRH related to drinking water and sewage were transferred to the ministry of human settlements and public works (SAHOP), which was more oriented around the development of urban services (Pineda et al. 2002). As a part of a program to decentralize the duties related to urban water management, in 1980 the management of some urban water supply systems was delegated to the states, and in some cases some states transferred the responsibilities to the municipalities. In 1982, the responsibilities of the hydraulic infrastructure of the SAHOP were transferred to the urban development and ecology ministry (SEDUE), and in the same year the decentralization of the urban water management systems started to take place. Due the lack of planning and a bad tax system, the municipalities who overtook the duties in the management of the urban systems did not have enough resources to provide good service. By 1988, in 21 of the 32 states in Mexico the responsibilities for urban water systems had been transferred to the state government, and in 11 states had been transferred directly to the municipalities (Pineda et al. 2002).

On 16 January, 1989, during the government of President Carlos Salinas de Gortari, CONAGUA was created as decentralized organisation in charge of designing water policy, formulating the national water program, developing potable and sewage water systems and treatment, developing a public registry of water rights, among others (Wilder et al. 2010). Under the regulation by CONAGUA, new guidelines for water and the water treatment sector were defined; the new guidelines had five main goals: 1. To provide legal capacity and own patrimony to the water operators so they could become decentralized and autonomous enterprises at a state or municipal level. 2. To democratize the administrative councils in which citizen representation and participation was included. 3. To generate the necessary measures to assure the financial resources obtained from the service bills were reinvested in the service itself, and not in other areas outside the water service area. 4. To determine and approve the prices of water service by directive councils inside the water service organisations, and not by the local legislations. 5. To ensure financial self-sufficiency and greater technical and administrative capacities of the water organisations so it would be possible to improve the service and to offer more competitive salaries to their personnel (Pineda et al. 2002).

During the decade of the 90s, the World Bank, the Inter-American Development Bank and the International Monetary Fund pushed several Latin American countries, which had failed in providing proper water and sanitation services, towards implementing various forms of privatization in the water sector (Brakin et al. 2006). Under this context, in Mexico the CONAGUA started a technical assistance program, National Potable Water, Sewage and Sanitation, with the main goal of developing plans and projects to build the necessary infrastructure and to consolidate the operative bodies. In order to finance this program, Mexico was granted loans from the World Bank (300 and 350 million USD) and the Inter-American Development Bank (200 million USD).

In order to get the loans mentioned, Mexico was pushed to make legal reforms in order to allow privatization policies in the water sector (Pineda et al. 2002; Ozuna et al. 2000). Because the Mexican Constitution in its article 27 states that water belongs to the nation, modification of the constitution and promulgation of a new law in water was necessary to allow private propriety. On the first of December 1992 the National Water Law (NWL) was published in the Diario Oficial de la Federación, replacing the old federal Water Law. The new law was focused on the participation of the private sector, allowing the possibility of granting private sector concessions to the for extracting and commercializing water for 5 to 50 years, and the creation of water transfer rights. CONAGUA (Zomosa-Signoret et al. 2007; Saade et al. 1998).

4.1.4 Water Management in Guadalajara

The actual water supply management structure in Guadalajara was born as a consequence of the demographic growth Guadalajara suffered during the first half of the 20^{th} century; during that period, water demand increased causing deficiencies in water supply. In 1950, after a petition was issued to the governor of Jalisco, the federal government financed the installation of six new wells in the Tesistan valley in order to assure the water supply for the city. At the same time, the municipality of Guadalajara requested a credit from the National Bank of Urban Mortgages and Public Works (Nowadays Banobras) to improve the water supply and drainage systems of the city. In order to assure the payment of this credit, the congress of the State of Jalisco created, in 1952, the Board of Potable Water and Sewer Services. This board had the responsibilities of administering, operating, conserving and improving the water supply system and the sewer network inside the municipality of Guadalajara. The administrative structure of the board was composed of a council, the maximum authority, made up of five persons, representatives of the government of Jalisco, the municipality of Guadalajara, the national bank of Mortgages and the users; one director, and three managements: administrative management, operation management and qualification and cadastre management (Jalomo et al. 2011).

As a result of urbanization of the city in the decade of 1970, the urban sprawl of Guadalajara reached the municipalities of Zapopan, Tlaquepaque and Tonalá, making necessary agreements between the four municipalities for the water supply of the MZG. In 1978, the congress of the State of Jalisco issued the law “Services of Potable Water and Sewer,” in which it contemplated the creation of an organisation responsible for the implantation, operation, administration and improvement of the potable water and sewer systems in the MZG. This new organisation, SIAPA, was conceived as a decentralized organisation with legal status, its own financial resources, and independence in the decision making process. In the beginning, and until the reforms of 2002, SIAPA was run by an administrative council formed by a General Director assigned by the Governor of Jalisco, representatives from the four municipalities that composed the metropolitan zone of Guadalajara, the Minister of Urban and Rural Planning, The Minister of Finance, a representative of the Chamber of Urban Property of Jalisco, one representative of the two biggest unions, and finally a representative of the further municipalities that would be integrated into the system. As one of its main goals, SIAPA was created to increase water supply and service coverage, to treat water and to promote rational use of water. In order to accomplish these goals, six managements were created, Technical management, Administration and Control Management, Administrative Management, Treasury Management and Operative and Maintenance Management (Regalado et al. 2006; Jalomo et al. 2011).

After the modification in the constitutional article 115 in 1983 and with the enactment of the National Water Law in 1992, the congress of Jalisco promulgated the Water Law of Jalisco and its Municipalities in 2000; in this law the municipalities were given the responsibility for the services of water supply, sewer, drainage, treatment and deposition of their wastewater. With this new law SIAPA underwent a restructuring; the administrative council was reorganized so that the municipalities gained more control while the representation of the state government diminished. The new administrative council was integrated by two representatives of each municipality of the ZMG and by three representatives of the State of Jalisco. One main change in the organizational structure of the "new" SIAPA, was that the designation of the director of SIAPA was no longer a responsibility of the Governor of Jalisco; instead, the position is elected by all members of the council (Regalado et al. 2006; Jalomo, et al. 2011). As a consequence of these changes, the structure of SIAPA was reorganized, with the creations of new departments (figure 4.3).

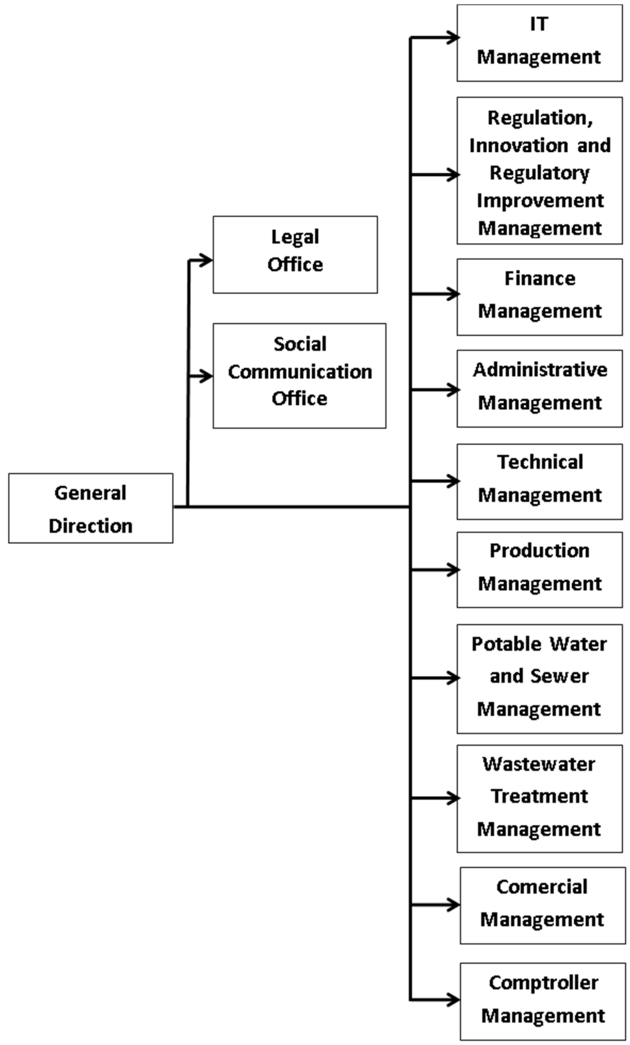

Figure 4.3: Organogram of SIAPA (Source: SIAPA)

4.1.5 SIAPA today

At present, SIAPA is the second biggest water supply company in Mexico, after the Water System of Mexico City, supplying over 80 % of the population of the metropolitan area (2011), and is responsible for over 98 % of the domestic water supply coverage of the city (SIAPA 2012). SIAPA has the main responsibilities for water supply, wastewater collection and wastewater treatment for the city of Guadalajara (as is stipulated in the Mexican constitution and the national water law as the new duties of municipal governments). In order to accomplish these responsibilities SIAPA manages a large infrastructure to extract, sanitize and distribute water for domestic, commercial and industrial consumption; and to collect, treat and allocate wastewater. The figure below is presents the water cycle for the city of Guadalajara, in which this infrastructure is pointed out (figure 4.4).

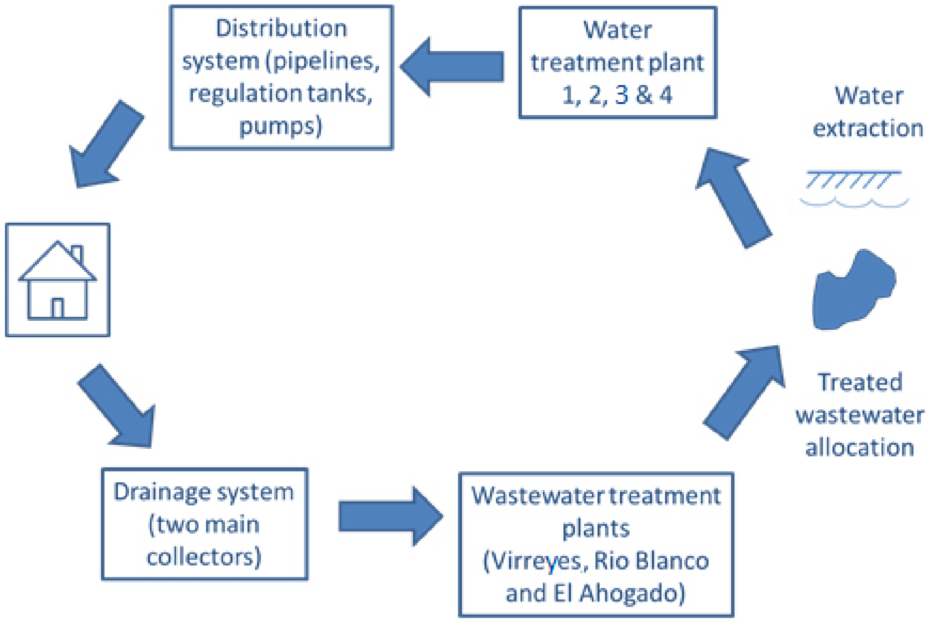

Figure 4.4: Hydrological cycle for the city of Guadalajara (Guzman et al. 2003, SIAPA 20012A)

As was previously mentioned, Guadalajara possesses three main water-supply sources: Lake Chapala, Ing. Elias Gonzalez Chavez dam, and aquifers. Water is extracted from Lake Chapala through an extraction plant which has six extraction pumps, each with a capacity of1.5 m^3/sec per second; usually only 5 pumps are in operation while one is used as backup. Before the water is pumped, it is filtered in order to remove big objects which could damage the pumps or block the ducts. After filtering, the water is pumped and transported to the city via one closed aqueduct with a length of 42.4 kilometres, a diameter of 2.1 metres and transport capacity of 7.5 m^3/sec. Water is pumped to a height of 138 metres at the middle distance between Chapala and Guadalajara, and then is delivered by gravity to treatment plants 1 and 2. Meanwhile, water extracted from Ing. Elias Gonzalez Chavez dam is transported by open canal to treatment plant 3 and then delivered to treatment plant 2 and 3. Water treatment plant 4 treats water extracted through deep wells located in the aquifer of Toluquilla (Guzman et al. 2003; SIAPA 2012A).

In the treatment plants, water is filtered, suspended solids are removed and chlorification is applied before the water is injected into the distribution system where it is redirected by several pumps until it reaches the final user, through 7,974 km of pipelines. After the water has been used, wastewater (grey water in case of the domestic sector) is collected through the drainage network and transported into two main collectors; wastewater produced in the northeast, southeast and the zone near the airport is treated in the El Ahogado wastewater treatment plant. This plant only treats an amount of 1.9 m^3/sec, the rest is disposed into the Santiago River without any treatment because the planned wastewater treatment plant Agua Prieta is not yet in operation.

Currently, SIAPA supplies water only inside the municipalities of Guadalajara, Zapopan, Tlaquepaque and Tonala; however, due to urban sprawl the urbanized area of the city has already reached the suburban municipalities of Tlajomulco de Zuñiga and El Salto. It is important to mention that the administrative council of SIAPA has the permission to enter into new agreements with new municipalities in order to take over water supply, and wastewater recollection and treatment from these municipalities, which means that the coverage of SIAPA may grow significantly in the coming years (Jalomo et al. 2011).

4.1.6 Legal framework of the Mexican water management

The legal framework of water management in Mexico is based directly on the Mexican Constitution, which in article 27 stipulates that the property of water and land located within the limits of the Mexican territory belongs directly to the nation, which had and has the right to transfer the domain of both to particulars, constituting the private property.

With this modification in the constitution, the new NWL was promulgated. In its last version, the NWL contemplates water management for urban/domestic use in a general point of view on its articles 9, 12 bis 6, 14 bis 5 and 20; and more specifically in its Title six "Uses of Water", chapter I "Urban/Public use", articles 44, 45 and 46.

Article 9, in section XIII specifies that it is the responsibility of CONAGUA to foment and support urban/public water and drainage services, water and wastewater treatment, water recirculation and water reuse in the national territory. It will coordinate these tasks with the governments of the states, and through them, with the municipalities. This will not affect the regulation, authority and responsibilities of the municipalities and states in the coordination and provision of the referred services.

In summary, article 44 mentions that the exploitation and use of superficial or subterranean water by water and sewage systems of the Federal District (Mexico City), the states and municipalities, will take place by direct assignment of CONAGUA; these assignments will remain even if the systems are managed by public or private entities. The treatment of wastewater produced by public/urban activities, prior allocation in water bodies, property of the nation, is responsibility of the public or private entities which offer domestic/public water supply service; waste water treatment must be performed conforming to the official Mexican norms. The agreements between municipalities and/or states in order to offer public service of potable water, drainage and wastewater treatment will be directly responsible for the accomplishment of the duties determined by CONAGUA.

Article 45 stipulates that the exploitation and use of the assigned water for Urban/public use, including wastewater, from the extracting source or delivery by CONAGUA, to the allocation site, is responsibility of municipal authorities. The use of this water could be made through public or private entities in charge of the service.

Article 46 mentions that CONAGUA could carry out the previous agreement with state governments in part or in full, and through them with the corresponding municipalities, works for collecting or storing, conducting and, if it is the case, treating the water supply, using federal funds or other funds with the guarantee of CONAGUA.

Finally, article 47 and 47 bis stipulate that the wastewater discharges into national goods or its infiltration in the soil which can pollute the subsoil and aquifers, will be governed by Title Seventh "Water pollution prevention and control and environmental damage responsibility" of the NWL. Moreover, CONAGUA will promote the use of wastewater by the municipalities, water management entities or third parties; also CONAGUA will promote among the public, private and social sectors, the efficient use of water in urban settlements, the improvement of water management, and actions to handle, preserve, conserve, reuse and restore wastewater produced by public/urban activities.

4.2 Water sustainability index results

The aggregation method selected to build the water sustainability index was the weighted geometric mean. As the reasons for selecting this method were already explained in the previous chapter, in this chapter I am only going to focus on presenting the results.

As was mentioned before, it was expected to determine the weights used in the index with the Delphi method, which determines weights based on the opinions of experts on the field. Several questionnaires were sent to more than 20 experts working in the academic field in NGOs or at governmental entities. However, the level of participation and involvement was extremely low such that the feedback obtained was not detailed enough to be used. The problems experienced during the survey included lack of responses, and poor quality information or opinions, such as "Is a previous condition water is available with enough quality for urban supply. Normally, it is expected that groundwater has good quality. Surface water requires, normally, treatment to reach the enough quality to be potable", giving a value of 0 to the water quality indicator. Therefore, at the end it was decided not to use the Delphi method to determine the weights' values. Using the same approach as in the water quality index, the weights were determined based on a grading table built according to three aspects: relationship with the water supply cycle, the relationship to the population's well-being, and the direct impact to the local/regional ecosystems. The grading table is presented below (table 4.1).

Table 4.1: WSI's weights grading description

Description	Grading
Not directly related to water distribution cycle but key parameter in sustainable development	1
Related to the water distribution cycle but not related with the population well-being	2
Related to the water distribution cycle and related with the population's well-being but no direct impact on the environment	3
Related to the water distribution cycle and related to the population's well-being with a direct impact on the environment	4

The eleven indicators that compose the WSI were graded according the table above, and afterwards the relative weights were calculated by dividing each grade by the sum of the grades given to all indicators. The indicators' weights are presented in table 4.2.

Table 4.2: WSI Indicators with weights

Indicator	Weight
1-Gini index	1
1-Patrimonial poverty	1
GDP per capita	1
1- % Of water loss during distribution.	2
% of treated wastewater	4
% Of houses connected to water supply system	3
% Of houses connected to drainage system	4
Income/expenses	2
Water availability	4
Water consumption per capita	4
Water quality index	4

4.2.1 Water sustainability index in Guadalajara from year 2000 to 2009

After collecting all necessary data for each index, and performing all needed statistical analysis, the water sustainability index was built. The final results are presented in the figure 4.5.

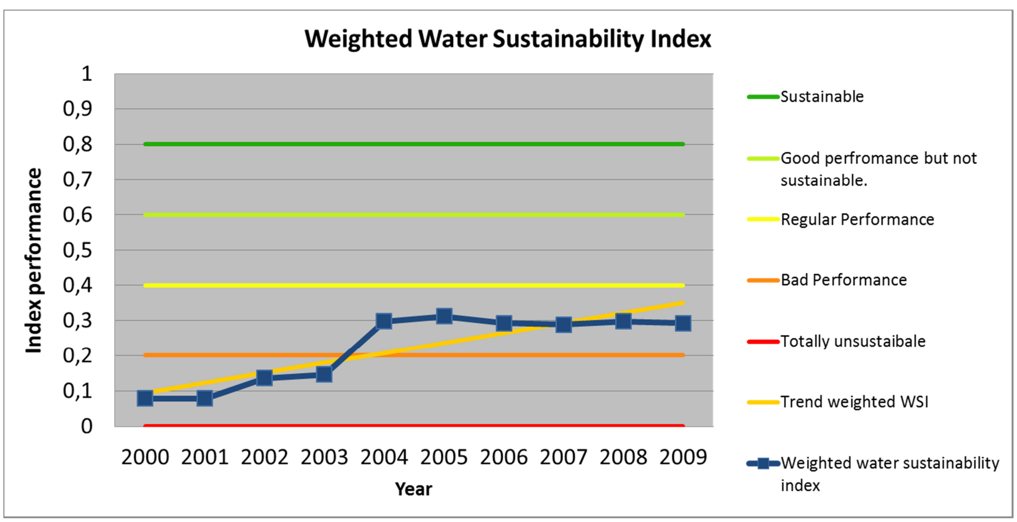

Figure 4.5: Water Sustainability Index of domestic water supply in the city of Guadalajara

Most of the years, the sustainability of the domestic water supply in the city of Guadalajara presented a performance between bad and regular, remaining relatively stable and not showing any improvement since the year 2004; only an improvement from 2000 to 2004 was presented. However that does not mean all indicators presented a bad performance, due to the characteristics of the geometric mean used as the aggregation method, if one or more indicators have a result near to 0 (or totally unsustainable) it is immediately reflected in the final results, lowering it drastically. Figure 4.6 presents the performance of all indicators without weights during the evaluation period.

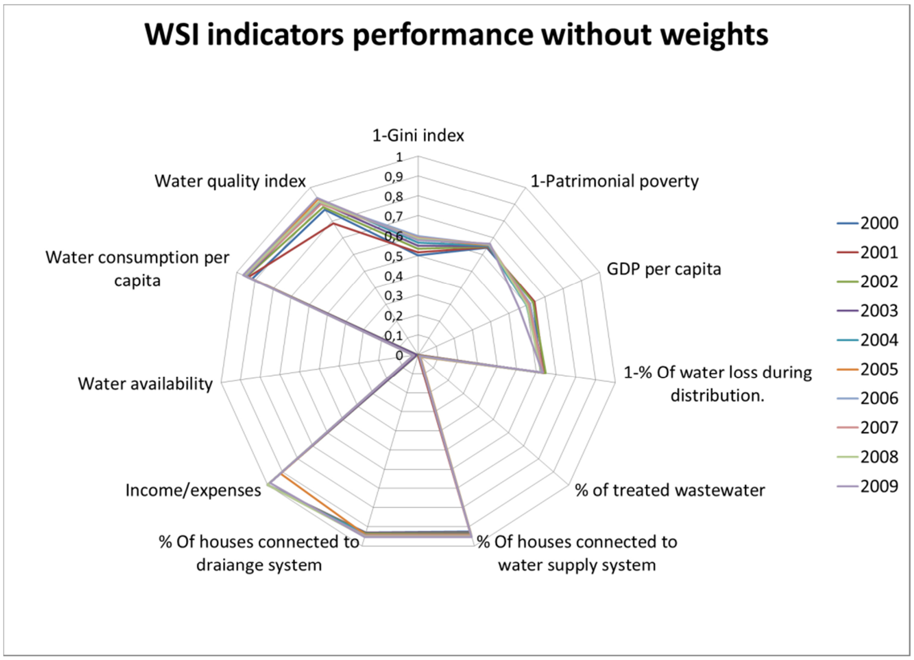

Figure 4.6: WSI indicators performance without weights, evaluation period of year 2000 to 2012

In figure 4.6 it is clear that two indicators are responsible for the overall low performance of Guadalajara: water availability and percentage of wastewater treated, which can be considered totally unsustainable. Moreover, all socio-economic indicators together with the percentage of water loss in the distribution system presented a regular result. Only indicators such as the percentage of population connected to water supply system, the percentage of population connected to the drainage system, and the overall water consumption per capita can be considered, if not sustainable, trending in the direction to be sustainable in a short period of time. In the special case of water quality, even though the overall result is close to the ideal result of 1, some indicators with high relevance to human health presented a regular result, and therefore a closer investigation of the indicators is always needed.

As was explained in Chapter 2, one of the main problems of using arithmetic mean indices for environmental sustainability assessment, such as in the cases of the ESI and EPI, is the eclipsing of bad performances of indicators by the good performance of the rest, causing the incorrect conclusion that the overall performance does not present any problem at all. This disadvantage can be solved by the use of the geometric mean as the aggregation method. Figure 4.7 shows the water sustainability index for Guadalajara calculated with the arithmetic mean and compared with the index previously calculated with the geometric mean; it is important to mention that both indices are using weights in the indicators. It is clear that the final result when the arithmetic mean is used seems to be much better than using the geometric mean when in reality it is not. This is because nine of the 11 indicators are eclipsing the performance of water availability and wastewater treatment which were totally unsustainable; a case where two of the most important indicators have a final result near to 0, cannot be considered a good performance. This may lead to a loss of perception about the main issues, causing selection of the wrong public policies.

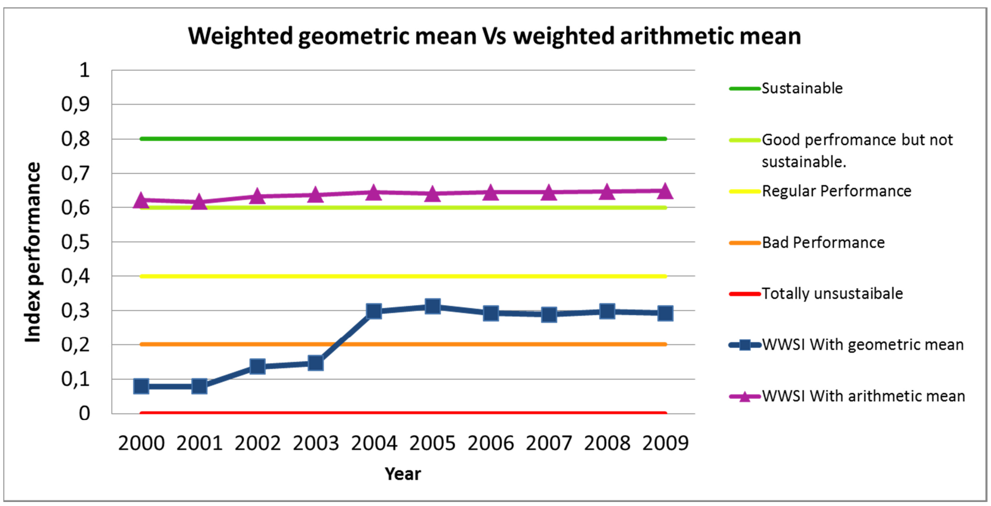

Figure 4.7: WWSI calculated with the geometric mean Vs. WWSI calculated with the arithmetic mean

Another advantage of using the geometric mean instead of the arithmetic mean is that the first is more sensitive to changes in the indicators; this situation is clearly exemplified in the first four years of the evaluation period where a slight improvement in the indicators were reflected by an improvement of 58.4 % in the final index from 2001 to 2004, while using only the arithmetic mean only caused an increase of 4.3 % (the same phenomenon is presented in the water quality index used on this research). Having a more sensitive tool is extremely important for decision makers because they can react faster if they perceive better changes in the indicators. The reason for this sensitivity is because the geometric mean reacts logarithmically to changes in the indicators while the arithmetic mean does it linearly. Moreover, if one pays attention to the data it is possible to see that from 2005 to 2006, a slight decrease in sustainability was presented using the weighted arithmetic mean while using the weighted geometric mean caused a slight increase in sustainability; the opposite situation was presented from 2006 to 2007, proving what Ebert and Welsch stated in their study (Ebert et al. 2004).

Finally, in figure 4.8 a comparison between the weighted geometric mean and the un-weighted geometric mean is presented. Basically, no difference in the behaviour of the final index trend was observed if specific or equal weights were used. However, better performance was observed if equal weights were used rather than specific weights. This situation reflects the influence of the weights in the final index result, but clearly proves that the index behaviour is solely affected by the indicators' performance.

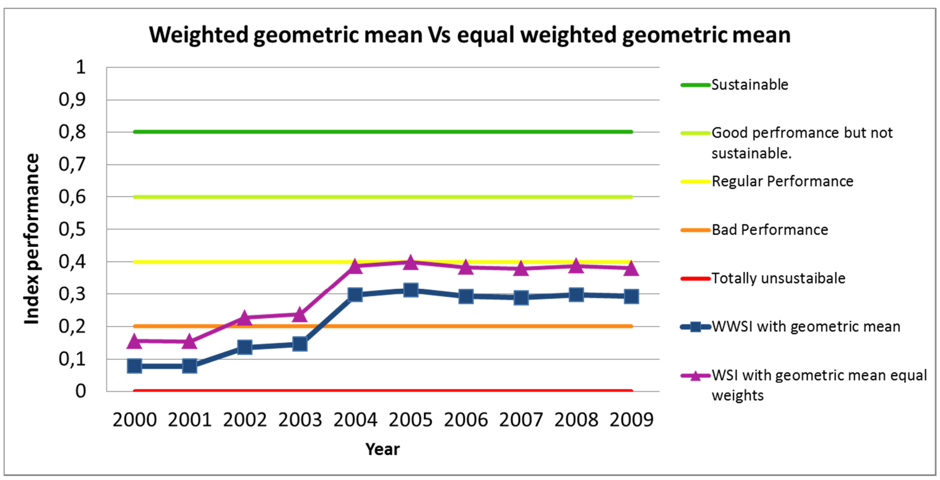

Figure 4.8: Comparison between the weighted geometric mean and the un-weighted geometric mean

It is important to mention that the sustainability assessment should not stop with the calculation of the final index; rather, for each indicator, a deep analysis of their individual performance should take place. A detailed explanation of each indicator's results will be presented below.

4.2.2 Indicator Results

4.2.2.1 Water availability

Guadalajara has three main sources of water supply: Lake Chapala, the most important source supplying around 55 % of the water consumed by the city; Atemajác and Toluquilla aquifers, supplying 40 % of the water; and finally, the Ing. Elías González Chávez dam (also known as Zurda-Calderón dam), supplying 5 % of the water.

Lake Chapala and the Atemajác and Toluquilla aquifers are by far the main water sources of Guadalajara, hence their importance of evaluating water availability in those sources. Unfortunately, for the case of water availability in the aquifers, there exist no reports, analysis, prognosis or studies in which we can obtain the information regarding the actual water levels of the aquifers. As was mentioned before, the responsible entity for regulating water extraction, determining water availability and monitoring the status of water bodies in Mexico is CONAGUA; however, after information on water availability in both aquifers was requested, the answer obtained from CONAGUA was “Both aquifers are under the condition of overexploitation, without any possibility of volume increments”; nonetheless, no information about the actual water level in either aquifer was given. For this reason, we consider water availability from the aquifers of Atemajác and Toluquilla to be 0, in other words, Guadalajara is already extracting more water than is possible to draw from the aquifers without affecting the local ecosystems.

Figure 4.9 shows a historic water volume register in Lake Chapala from 1934 to 2010. In this chart, two critical periods have occurred in the last 80 years where the volume of the lake decreased drastically, reflecting the two most significant crises the lake suffered in the last 100 years. The first crisis occurred during the period 1945 to 1958, in which a lower than average rainfall combined with extraction from Lake Chapala for electricity generation (around 520 hm^3/year) and irrigation (215 hm^3/year) caused the lake to reach the lowest level ever registered (953.98 hm^3) in July 1955 (Wester, et al. 2009). The second critical period was from 1999 to the end of summer 2003, registering a low volume level of 1145.16 cubic hectometres in July 2002. After the second drought period the volume of Lake Chapala started to increase continuously because of the increase in precipitation during rainy seasons over the local basin.

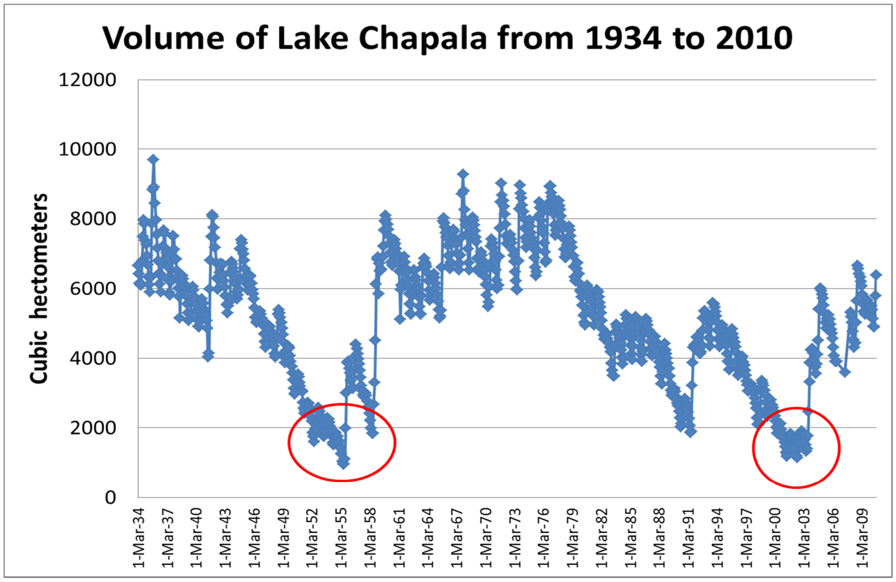

Figure 4.9: Historical monthly water volumes of Lake Chapala 1934-2010 (Source: IMTA 2009)

In figure 4.10, the total yearly rainfall inflow to Lake Chapala for the period from 1934 to 2001 is presented. If we compare figure 4.9 and figure 4.10, it is clear that both crises in Lake Chapala occurred when low pluvial precipitation occurred in the area.

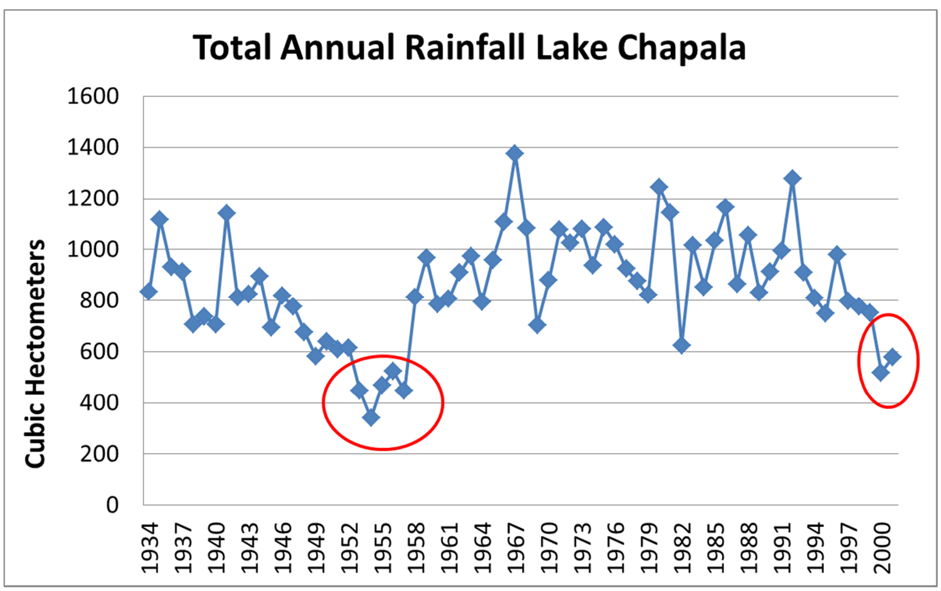

Figure 4.10: Total annual rainfall in Lake Chapala (Source: IMTA 2009)

Figure 4.11 shows the behaviour of the volume of Lake Chapala during the evaluation period; in this graph, the minimum volumes registered in each year from 2000 to 2009 are presented and compared with the natural volume capacity of Lake Chapala (4500 Hm^3) (Cotler et al.

2006), the minimum permissible volume in the lake (2000 Hm^3) based on the agreement of the Lerma-Chapala basin Council and with the minimum volume registered in the lake from 1934 to 2010.

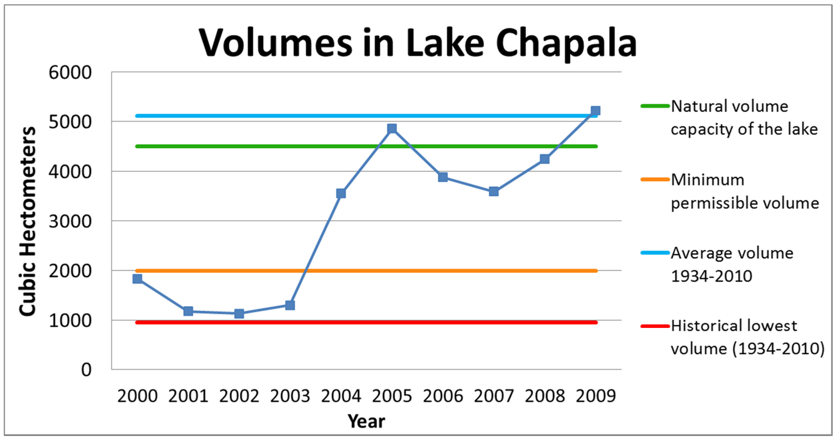

Figure 4.11: Minimum volumes in Lake Chapala 2000-2009 (Author's elaboration with data from IMTA)

This figure shows how the drought period started in the last part of the 90's, and reached its critical point in 2002. During the first few years of the last decade, the citizens of Guadalajara as well as the government had the fear that Lake Chapala could not recover its level and could become a seasonal lagoon. This fear caused an increase in people's awareness, which was reflected in political pressure to implement immediate actions to overcome this problem. This led to the agreement signed between the five federal states which belong to the Lerma-Chapala basin and the federal government, in which it was stated that a volume of 2000 Hm^3 must be assured in Lake Chapala during low water season.

After 2003, a positive trend can be seen; during last few years, water volumes increased with high precipitation levels. It is clear the lake has again reached average volumes, but this situation is unpredictable because the lake inflows from Lerma and Duero rivers are very poor, reflecting the dependency of the lake on good rainy seasons to maintain proper volumes; therefore, if low rain periods occur again, the lake could be endangered as it was during 1954 and 2002.

Figure 4.12 shows the minimum volumes of the Zurda-Calderón dam during the period 2000-2009. The active storage of the Zurda-Calderón dam is 78 hm^3 (sustainable) and the dead storage (unsustainable) is 2 hm^3 (CEA 2010). The behaviour of the dam during these years is similar to the one presented by Lake Chapala in the same period of time; that can be explained by the fact that the drought at the end of the 1990's and the beginning of the 2000's not only affected the local basin of Lake Chapala, but the mayor basin of Lerma-Chapala-Santiago as well.

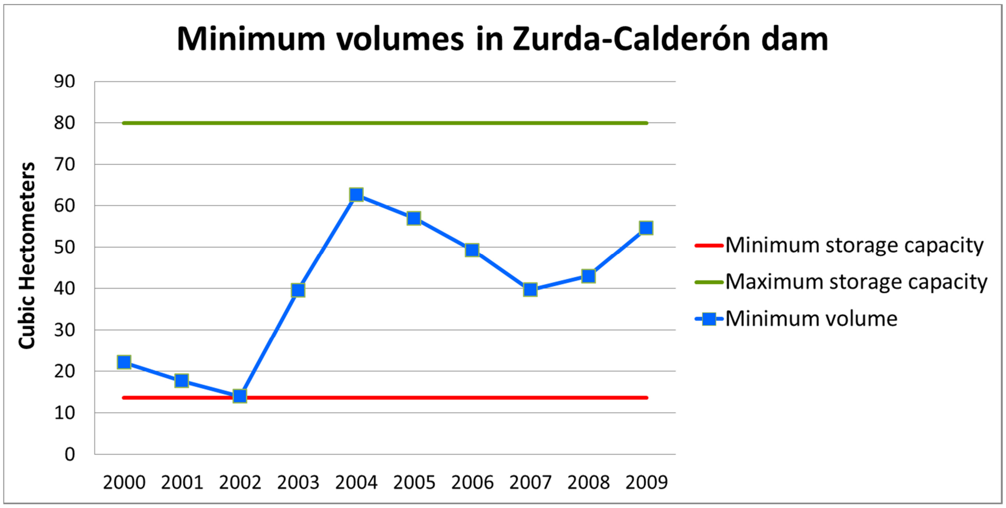

Figure 4.12: Minimum volumes in Zurda-Calderón dam (SIAPA 2011A)

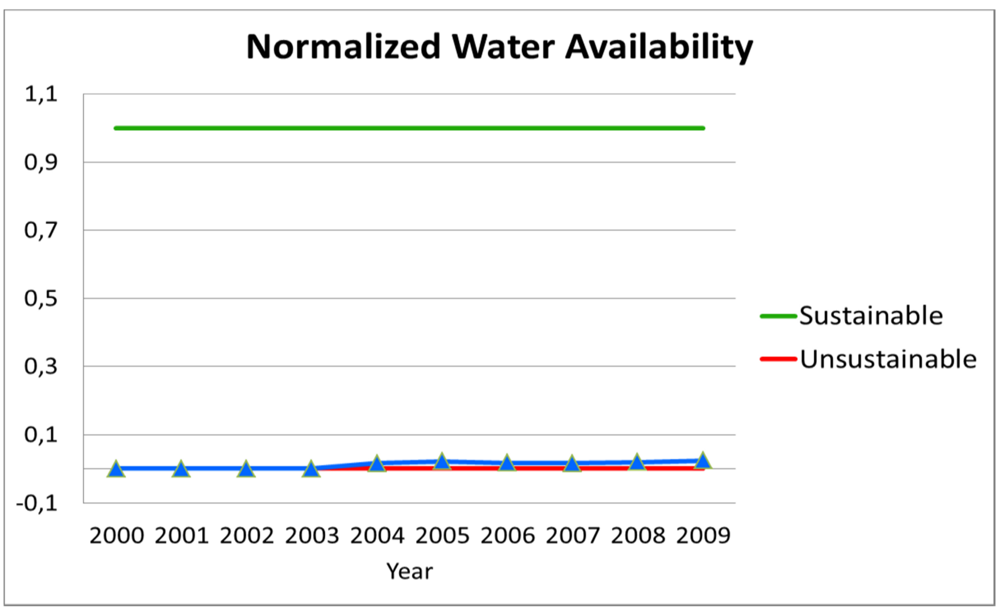

Figure 4.13: Total water availability after normalization

Figure 4.13 shows the normalized result of this indicator. The final result of this indicator shows a totally unsustainable performance during the complete evaluation period. This is explained by the fact that Atemajac and Toluquilla aquifers are over-exploited, making them unable to achieve a natural recharge during the raining season. Similarly, the volumes of Lake Chapala were below the permissible level of 2000 Hm^3 from 2000 to 2003 influencing the extremely low result at the beginning of the evaluation period. Nevertheless, a slight improvement was shown after 2004, explained by the increase in volumes of Lake Chapala and Zurda-Calderón dam in the following years. Guadalajara will never reach sustainability with respect to this specific indicator if the situation previously explained remains; only if aquifers' recharging actions are implemented then a considerable improvement in water availability may occur. One critical aspect of this direction is that there is no direct control over how much water is extracted by all the wells under concession, as CONAGUA does not have enough resources for auditing the real extraction. This gives the concessionaires the freedom to extract all water they want. Another important factor is that CONAGUA obligates all concessionaires to use the total amount of water under concession, in the case that the concessionaire uses less than the stipulated amount in a period of two years, the concession is cancelled; this policy does not allow the possibility of implementing water saving procedures that could lead to stress reduction in the aquifers (National Water Law, article 29 to 3 section VI).

4.2.2.2 Water consumption per capita

As was mentioned in the description of the indicators, the overall water consumption per capita is the one to be used in our index; however, it is considered important to also show and compare the real water consumption per capita in the domestic sector with the total water consumption per capita made by all sectors together. The overall water consumption per capita and the real water consumption per capita of the domestic sector in the city of Guadalajara are presented in Figure 4.14.

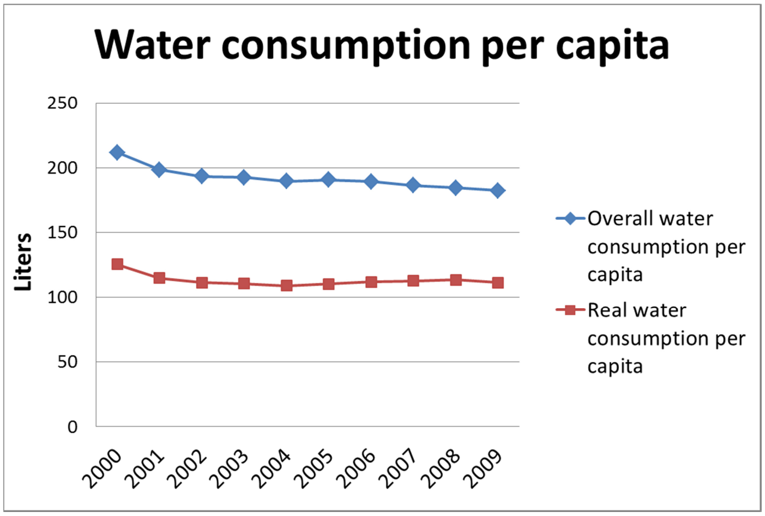

Figure 4.14: Overall and real water consumption per capita in the city of Guadalajara (Author's elaboration with data from SIAPA and CONAGUA; SIAPA 2010A, SIAPA 2010C, CONAGUA 2010A)

Figure 4.14 shows stable water consumption per capita in both overall and real water consumption per capita after 2002; this indicates that commercial, public and industrial water consumption also remained stable over those years. After 2002 the average overall water consumption per capita in Guadalajara was around 188 litres per day; this result is just 17 % above the 160 litres reported to be the total water consumption per capita of the city of Berlin in 2005 (Zikos et al. 2008). In the same way, the 113 litres average presented in figure 4.14 as domestic water consumption per capita in Guadalajara can also be easily compared with the domestic water consumption in cities known for having an acceptable domestic water consumption such as Berlin, with 110 litre per person per day in 2005, or Barcelona with 107 litres per person per day in 2009 (Zikos et al 2008; Aigües de Barcelona http://www.aiguesdebarcelona.cat/esp/compania/abastecimiento/evolucion_consumo.asp).

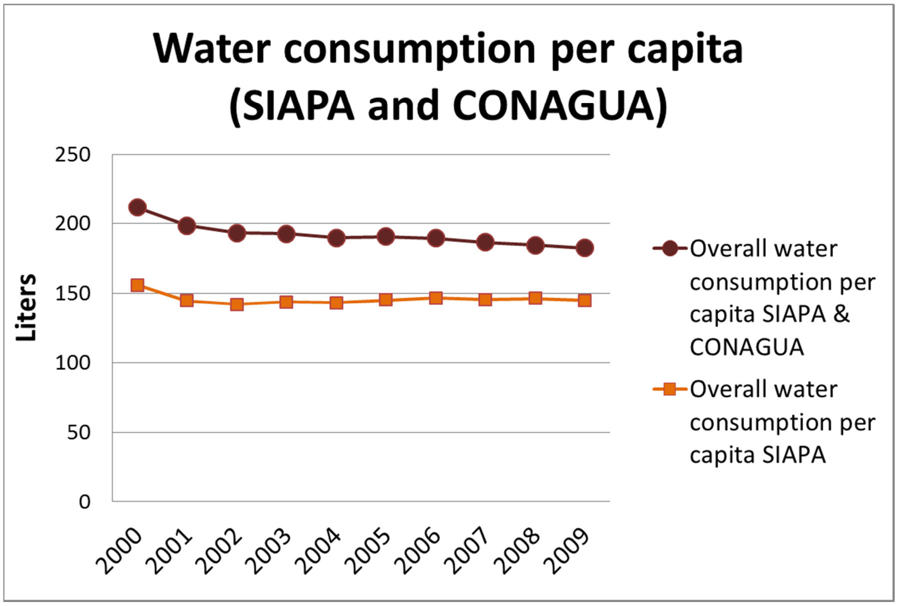

Figure 4.15: Comparison between overall water consumption per capita in the city of Guadalajara with data from SIAPA and data from SIAPA plus CONAGUA (SIAPA 2010A, SIAPA 2010C, CONAGUA 2010B)

Because SIAPA supplies 91 % of Guadalajara (Jalomo et al. 2011), a comparison between the overall water consumption per capita from SIAPA only and the overall water consumption per capita of the whole city (including the information from CONAGUA) is required. This comparison is presented in figure 4.15. The average of the difference between both estimates is only 18 %, even though 98.6 % of all water under concession by CONAGUA (excluding the water concessions granted to SIAPA) is used by the industrial and economic sectors and just 1.4 % of the water under concession is used by the domestic and public sectors. If the total amount of water delivered only by SIAPA is considered and it is divided by the number of users supplied by SIAPA, then the average water consumption per capita is around 160 litres per day, which is the same consumption reported in Berlin. These results prove that the lack of control of CONAGUA on the licensed wells leads to an increase in water consumption.

It is surprising how these results contradict the official position of CEA. The Government of Jalisco has always stated that the water demand per capita in Guadalajara is approximately 280 litres per day· On its website, CEA mentions that the water demand of the city of Guadalajara is about 13.06 m^3/s; they made this calculation considering the population of the city of Guadalajara was 4,095,853 inhabitants in 2005. Using these numbers, the water consumption per capita according to CEA can be calculated, resulting in 275.5 litres per day.

They have used this argument to support a new project for water supply in Guadalajara, which had the intention of replacing Lake Chapala as the main water source for the city; however, this project, called the Arcediano Dam Project, was severely questioned by a group of academic experts, NGOs and the population in general, in terms of the negative ecologic and health impacts this project would have caused.

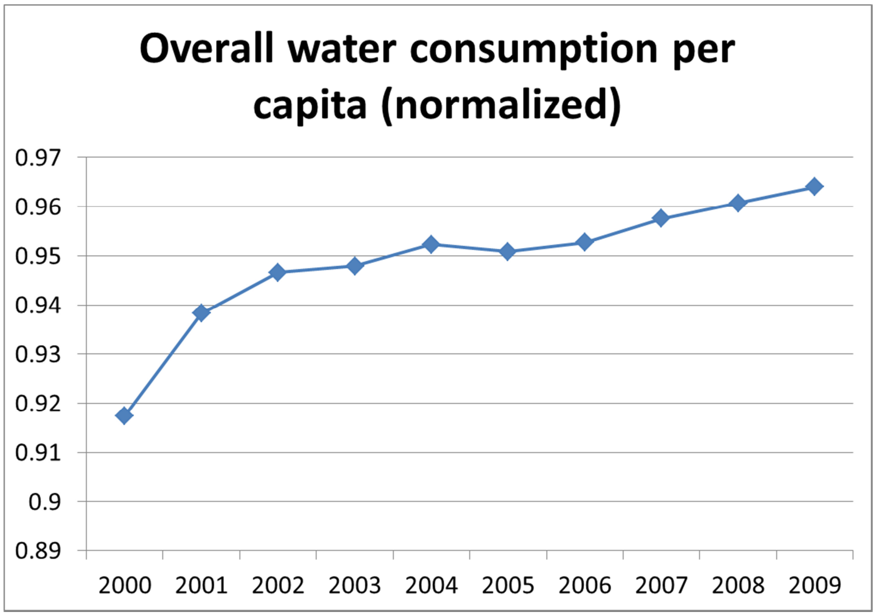

Figure 4.16: Normalized overall water consumption per capita

Figure 4.16 shows the normalized indicator. It is clear that the overall water consumption per capita in the city of Guadalajara can be almost considered sustainable; a positive trend is appreciated that gives us enough evidence to state that sustainability in this specific indicator can easily be reached. However, more water saving policies should be implemented, but not focused specifically on domestic consumption, since it was demonstrated that it has the same levels as the "sustainable cities." Instead, the commercial and industrial segments' water consumption should be focused on.

The low water consumption per capita in Guadalajara is explained by awareness of the final user about of the impact of high water consumption per capita to Lake Chapala, the main water source for Guadalajara. Supporting this assertion are the results obtained from a survey performed during the spring of 2008 in the city of Guadalajara in order to determine the perception of the final user regarding the water supply system. Another one of the objectives of this survey was to determine some of the technical characteristics related to water consumption in the dwellings in Guadalajara. Two of the specific questions asking in this survey were whether the households use some water saving techniques and if they possess water saving devices. The results obtained from this question was that only 53 % of the surveyed householders mentioned they use at least one water saving method and 18 % of the respondents have at least one water saving device; altogether, 64.67 % of the total population surveyed answered positive to one or both questions. The reasons given for the 72 % who answered they do not have a water saving device of not having it, were lack of awareness of such a device, lack of money, and lack of interest. The proportion of people from middle and upper socio-economical classes who possess water saving devices was higher than the lower socio-economical classes (none from the popular socio-economical class). Those people who answered that they implemented at least one water saving method followed the same socio-economical distribution as the population in general.

The most common methods/devices mentioned are presented in the figure 4.17.

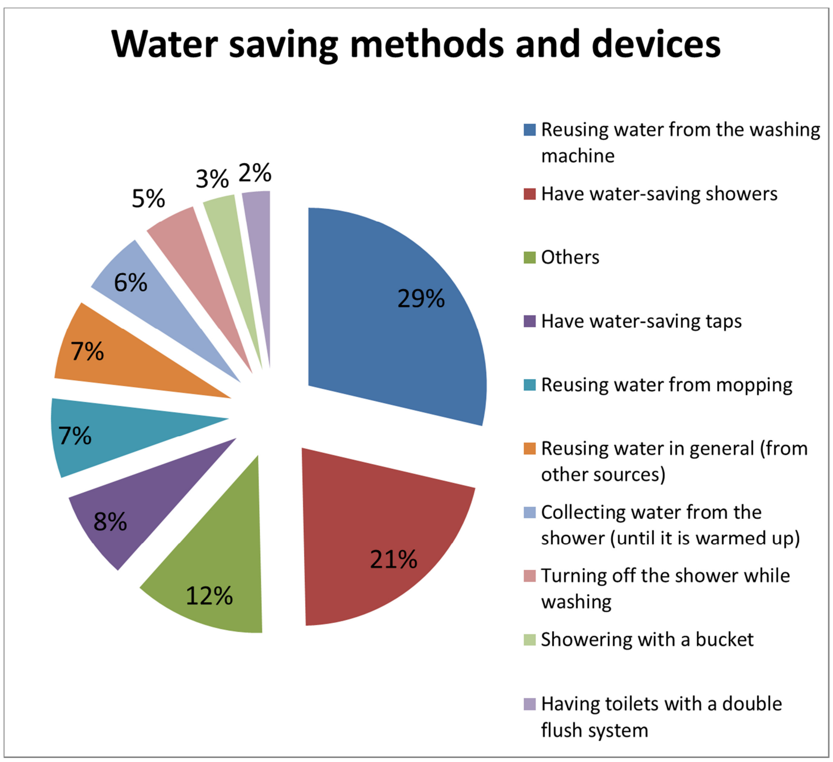

Figure 4.17: Most common water saving methods and devices mentioned in the survey (author's elaboration)

The most frequently mentioned method for saving water was the re-use of water from the washing machine. To collect water from washing machines to be re-used demonstrates the high level of water-saving conscience, due to the implications this activity represents. In order to collect the water, the person must unplug the wastepipe from the drainage and put it into a big container; that means to have a big container near the washing machine and to check that it does not overflow; some persons also added that they usually first wash white/light coloured clothes, and after that they use the collected water again for washing dark coloured clothes. To do everything described above represents an enormous effort, and it is only made if the person truly cares about saving water, even if for ecological or economic reasons. This specific answer was given mostly by people from lower socio-economical classes; 70.5 % of the persons who gave this answer were from lower socio-economical class; the other 29.5 % were middle class respondents. The information obtained from the survey reflects the awareness of the people regarding the problems in the water supply and the effort needed for saving water.

4.2.2.3 Water quality

Sixteen indicators were used to evaluate the water quality of two water treatment plants (please refer to table 3.2 of chapter 3), one supplied by Lake Chapala (water treatment plant 1) and one supplied by Elias Gonzalez Chávez dam (water treatment plant 3); and water extracted by the well system of SIAPA. The water quality was evaluated using an index specially developed for this purpose.

The water quality index (WQI) was composed of three sub-indices (water treatment plant 1, water treatment plant 3 and wells). Both the water quality index and the sub-indices used the weighted geometric mean as the aggregation model (for a theoretical explanation please refer to Chapter II).

Water quality index.

The weights for the water quality index were defined according to the percentage of water supplied by each source versus the total water supplied every year; that means that the weights changed every year with respect to the amount of water provided by each source in the same year.

Water quality sub-indices.

Each sub-index is composed of 16 water quality variables (Table 3.2) which are aggregated, as was mentioned previously, by the weighted geometric mean. In order to determine the weights of the variables each variable was graded from 1 to 5 according to the health impact of its presence/absence in water bodies. On table 4.3 the weights w_i for the variable are given including a brief description of the meaning of the grading system.

Table 4.3: Water quality variables' weights

Variables	Weight w_i
Ammonia Nitrogen	2
Arsenic	5
Benzene	5
Cadmium	4
Chlorides	2
Dissolved oxygen	1
Total dissolved solids	2
Faecal Coliforms	5
Fluorides	3
Lead	4
Mercury	5
Nitrates	2
Nitrites	3
Pesticides	5
pH	2
Turbidity	2

Where:

5 High health relevance: immediate high health impact like a source for epidemics, or intoxication due to high concentrations; or long term high health impact, like development of cancer due to long term exposure.

4 Medium health relevance: high health impacts in long term exposure with high concentrations; medium health impacts in immediate exposure or long term exposure with low concentrations.

3 Low health relevance: Low health immediate impacts; medium to low health impact in long term exposure.

2 Infrastructure relevance: Damage of water supply or water usage devices due to compounds in water.

1 Displeasure of the user: No health impacts, just displeasure for the final user due to water characteristics such as colour or taste.

After the weights were determined, they were normalized into relative weights w_i by dividing each weight by the sum of all weights.

On figure 4.18 a graphical overview of the water quality index results is presented.

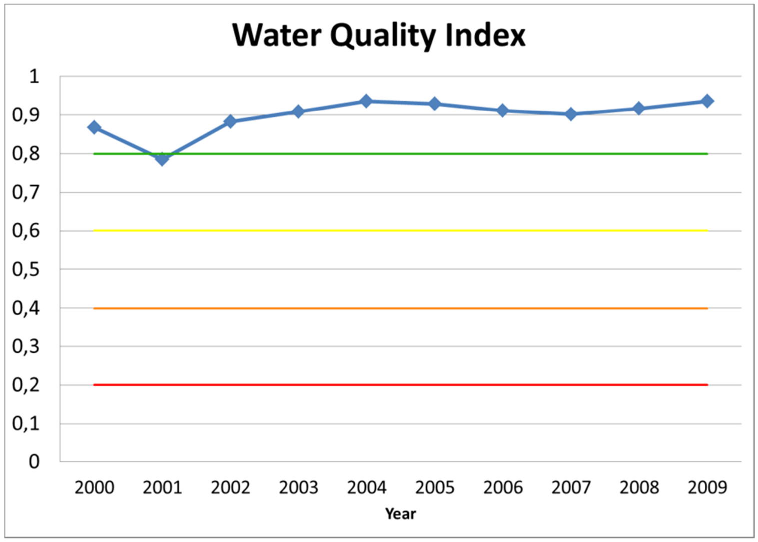

Figure 4.18: Water quality index

In this figure the grading of the water quality index was divided into five zones, from totally polluted to proper for human consumption.

The results presented indicate that water quality after treatment presented a good performance over the evaluation period; however it is worth mentioning that for some of the variables used just small amount of data was available and for the first years of the evaluation period no data for the sixteen variables was obtained; this situation is reflected in the final result of the index. In 2001 the lowest index result was mainly caused by low quality performance in Lake Chapala and in the wells. In the case of Lake Chapala, the biggest contributor was the level of fluorides, of which only around of 15 percent of the distribution lay inside the specification limit. On the other hand, the low performance on the wells was caused mainly by poor results in the variables of dissolved oxygen, faecal coliforms and turbidity. The results are presented in more detail in figures 4.21, 4.22 and 4.23.

During the water quality index development, the results were also aggregated with other aggregation methods in order to compare the results with the chosen one. The other selected methods were the un-weighted arithmetic mean, the weighted arithmetic mean and the un-weighted geometric mean. The comparison is presented in figure 4.19.

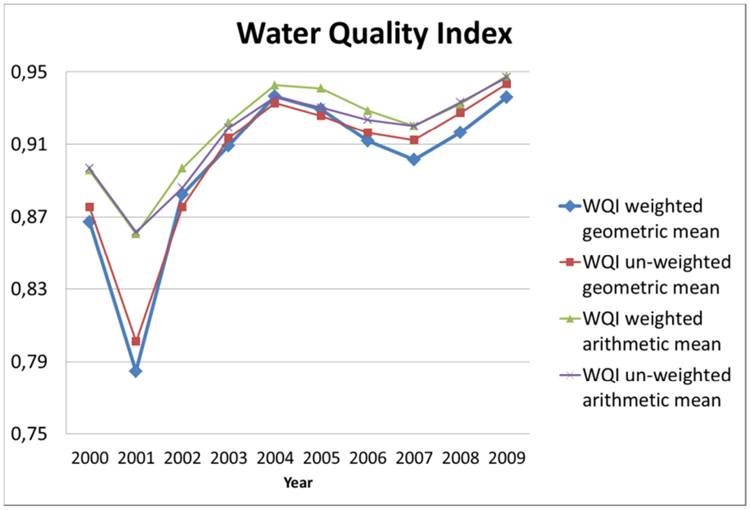

Figure 4.19: WQI using different aggregation methods

It is clear in figure 4.19 that a better interpretation of the water quality is achieved with the arithmetic mean compared to the geometric mean. This situation can be explained by the fact that lower x_i represent less influence on the final result in the arithmetic mean than in the geometric mean. That means an extremely low result in a single variable will impact the final result more if the geometric mean is used rather than the arithmetic mean, and this situation was clearly reflected in year 2001 where some variables (mainly fluorides in water treatment plant 1 and dissolved oxygen in wells) presented low levels. In other words, the use of arithmetic mean as an aggregation method may eclipse bad performance of some water quality variables if the majority of the rest of the variables presented an exceptional performance.

Moreover, from figure 23 we can also conclude that the weights do not play as much of a major role in the final result as does the selected aggregation method; however, a proper weighting system give the variables the relative importance that they have, allowing the avoidance of eclipsing.

Figure 4.20 shows the comparison between the WQI calculated using the process capability indices and using the means; for both cases, the weighted geometric mean was used as the aggregation method.

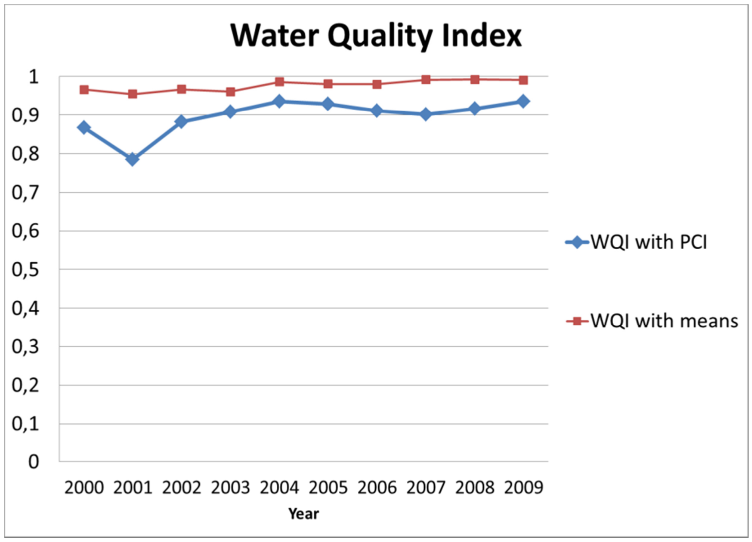

Figure 4.20: WQI index calculated with PCIs Vs. WQI calculated with means

In figure 4.20 an overestimation of the water quality is presented, even more in 2001 where the difference between the results of using both methods is more than 18 %. The clear problem using only the means for calculating the WQI is that only the first moment of the distribution is used which leads to the effect caused by the spread of the distribution and the shape of the distribution is ignored. Actually, most of the authors that use the means for calculating their own WQIs use the Gaussian mean, which assumes the variables follow a normal distribution, which rarely occurs in water quality indicators due to the fact that most of them are naturally bounded with zero. A second problem presented with using the means is that they may show an increase in water quality, when in reality the quality performance is decreasing; this situation is clearly exemplified on the water quality performance of Guadalajara from year 2006 to year 2007.

In the next three charts, the individual PCI result for each variable according to sampling location is shown.

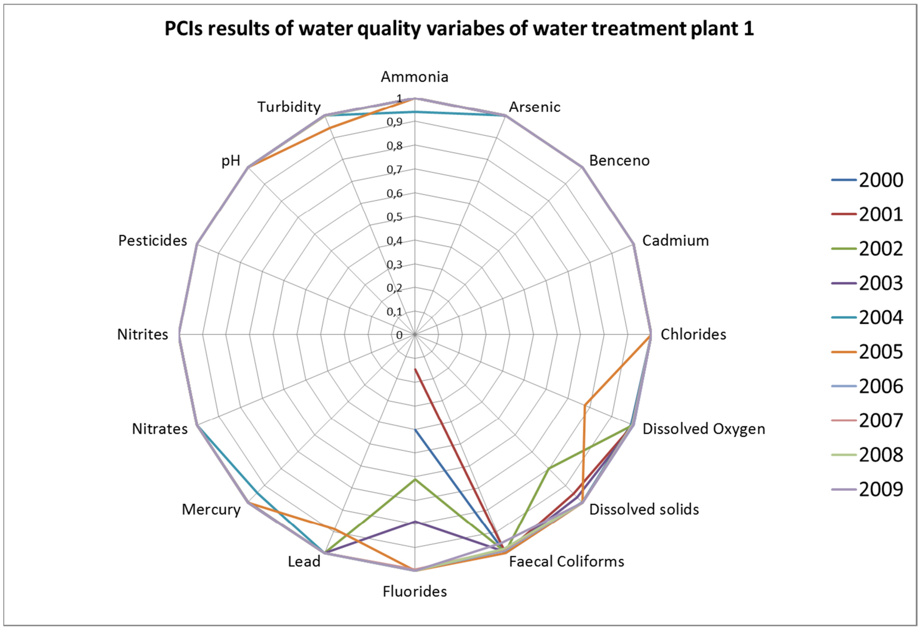

Figure 4.21: PCIs for water treatment plant 1 (years 2000-2009)

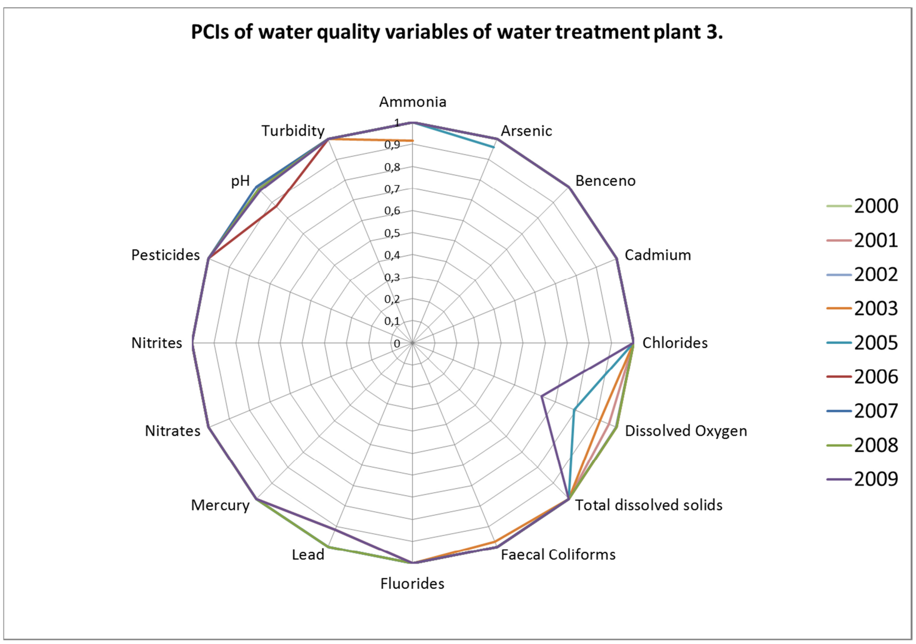

Figure 4.22: PCIs for water treatment plant 3 (years 2000-2009)

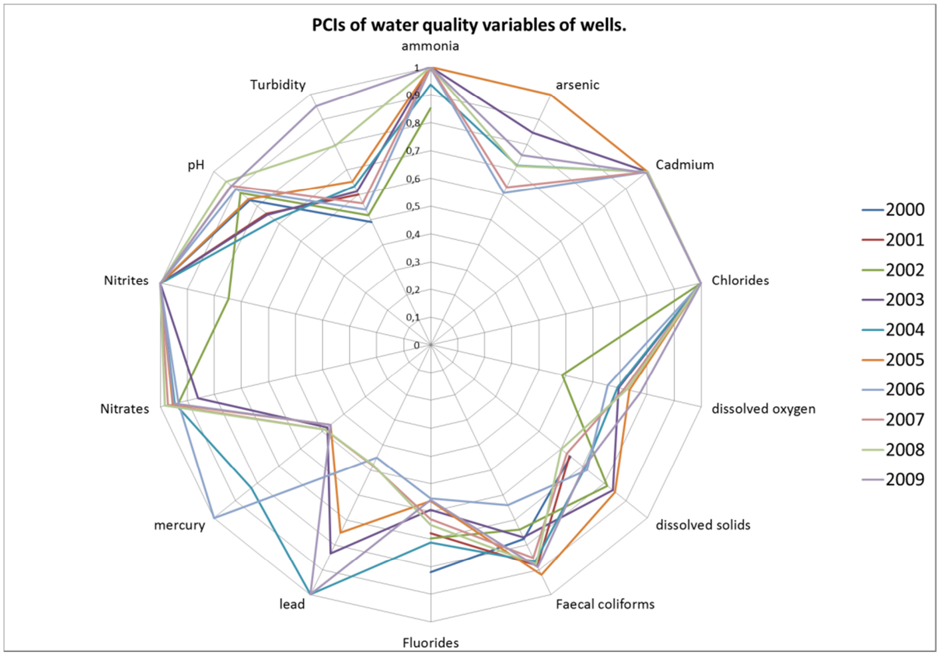

Figure 4.23: PCIs for wells (years 2000-2009)

In the case of water treatment plant 1, the variables with low quality performance were fluorides from 2000 to 2003 and total dissolved solids from 2001 to 2003. The high level of fluorides and total dissolved solids during the same period of time can be explained by the fact that during those years the level of Lake Chapala decreased considerably. For water treatment plant 3, dissolved oxygen was the variable which presented the lowest performance; mainly in the years 2001, 2003, 2005 and 2009.

However, what is really interesting about the information just presented is the water quality performance of the Toluquilla and Atemajac aquifers. Water quality in aquifers is commonly considered by many, including some academics, as pure water (not polluted); nevertheless, the performance of samples taken from the wells is fair and even sometimes had a very low quality. Contrary to what happened in the analysis made of the samples taken from water treatment plant 1 and 3, the samples taken from the wells present a low performance in several variables where turbidity, dissolved oxygen and faecal coliforms were the most significant, followed by arsenic, lead, mercury and dissolved solids. Presence of faecal coliforms in several samples taken from the wells can be explained by the filtration of faecal matter through the subsoil that leaked from obsolete drainage pipes or by poorly maintained septic tanks. Low levels of dissolved oxygen of subterranean water are expected, due to the low oxygenation level on subterranean water. Heavy metal levels above the specification, mainly arsenic, can be explained by the overexploitation of the aquifers; when an aquifer is overexploited, a salinization process begins to increase levels of arsenic in the aquifers; Guadalajara is also located near a volcanic zone (the Primavera forest which borders Guadalajara on the western part of the city is a well-known geothermal zone) where presence of arsenic in groundwater is not uncommon.

Overall, the water quality level of Guadalajara calculated based on the samples obtained from water treatment plants 1 and 3, and from the wells, is acceptable, but not sustainable. Nevertheless, this situation changes with the distribution system. Data supplied by SIAPA, figure 4.24, shows the results of the water quality analysis of samples taken from several points of the distribution system. The water obtained from these sampling points was supplied by water treatment plant 1.

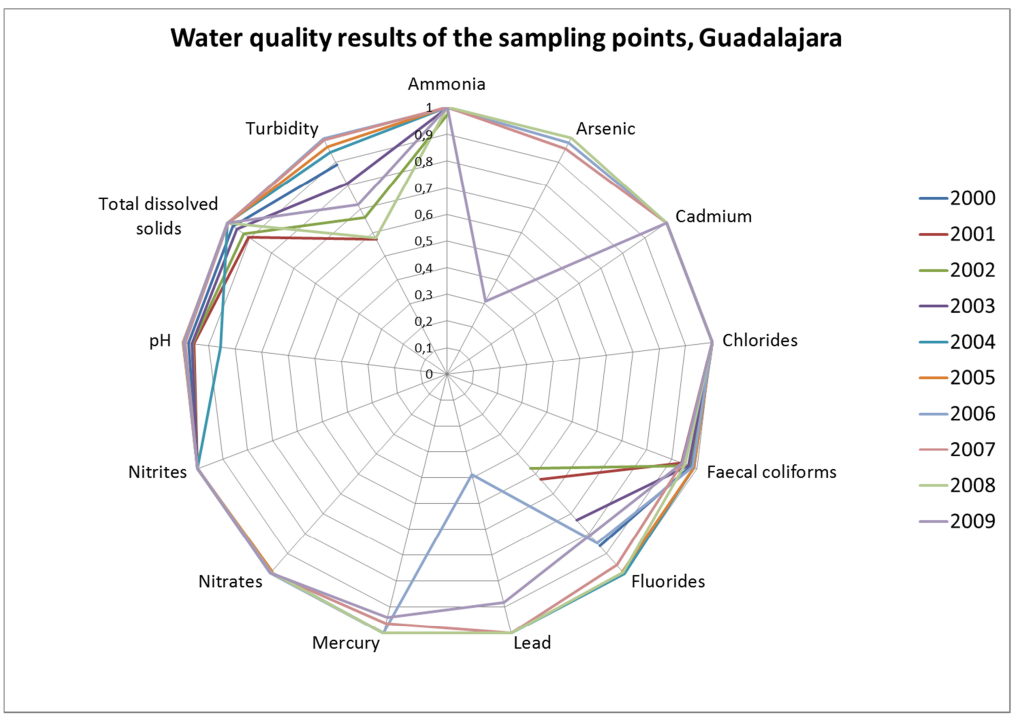

Figure 4.24: Water quality results of samples taken from the distribution system (water supplied by water treatment plant Nr. 1)

If we compare figure 4.21 and figure 4.24 (both showing water supplied by water treatment plant Nr. 1) we can clearly realize that a decrease in water quality had occurred in the distribution system. One issue of particular concern is the presence of faecal coliforms in the distribution system. After treatment in water treatment plant Nr. 1, from 2000 to 2008 an average of 99.2 % of all samples taken were negative in faecal coliform bacteria, and in 2009 over 95 %were negative. However, in the distribution system, an average of 96 % of the samples taken per year during the evaluation period was negative. This information shows, even with the treatment received in WTP 1, colonization of faecal coliform bacteria in the pipelines had occurred, or polluted water had filtered into the distribution system through deteriorated pipes; both scenarios are likely to have happened. Based on the state of the distribution system which today is over 44 % obsolete, filtration of pollutants can easily occur. Also, if we look at the turbidity level of the samples taken in the distribution system (figure 4.24) we can expect that a large number of particles are present in the water which makes it easier for bacteria to reproduce.

The only indicator in concurrence with the results presented after treatment in WTP 1 is the concentration of fluorides in water; which showed poor performance from 2000 to 2004.

One social aspect related to water quality is the confidence of the final consumer in the water supply. In Mexico, due to the low perception of the quality of water resources, a considerable proportion of Mexicans consume bottled water; therefore Mexico has recently become the biggest consumer per capita of bottled water in the world with 224 litres per year per person (Rodwan, et al. 2009). The city of Guadalajara is not the exception; the inhabitants of Guadalajara consume 2.23 litres per person per day, which represents 813 litres per year (Gomez Jauregui et al. 2009). This situation clearly reflects the lack of confidence of the people in the ability of the water supply entities to provide high quality water.

4.2.2.4 Percentage of population connected to water supply system and percentage of population connected to drainage system

As was mentioned before, the data from the 1990, 2000 and 2010 population and housing census, and the 1995 and 2005 population and housing counting were used to build a trend using two logarithmic functions (one from 2000 to 2005 and the other from 2005 to 2010). Figure 29 shows the result of houses connected to the water supply system and drainage system.

From 2000 to 2009 a continuous increase in the population connected to both services was observed. In the case of the water supply system, almost no change in the rate of increase was present; on the other hand, for population connected to a drainage system from 2005 to 2009 the rate increased from 2000 to 2005. The results of these indicators reflect the efforts of SIAPA and municipal governments to reach 100% connectivity for the population of Guadalajara.

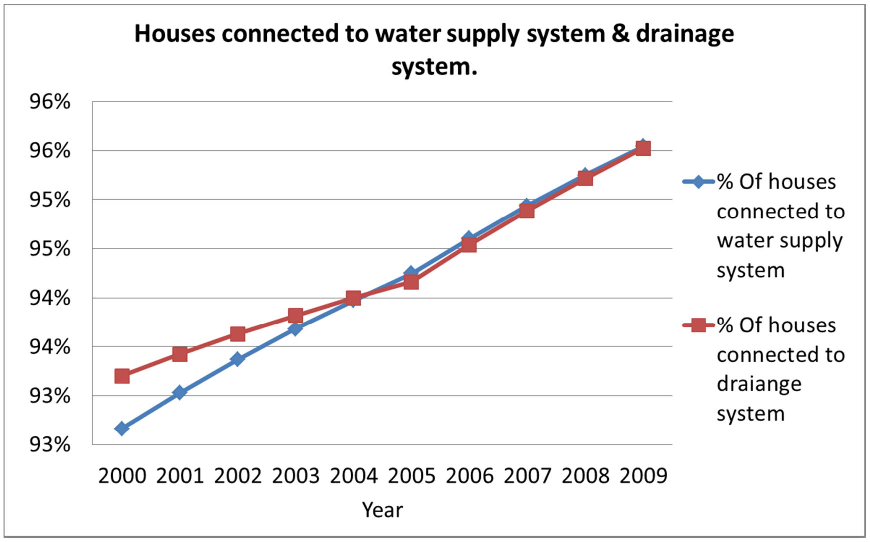

Figure 4.25: Percentage of houses connected to the water supply system and to the drainage system (author's elaboration with data from INEGI: www.inegi.org.mx/est/contenidos/Proyectos/ccpv/default.aspx)

4.2.2.5 Gini Index, Percentage of population living in patrimonial poverty and Gross Domestic Product (GDP) per capita

Gini index.

Data provided by the National Council for the Evaluation of Social Development Policy (CONEVAL), shows that the inequity levels measured by the Gini index in Guadalajara for the years 2000 and 2005 were 0,4944 and 0,4188 respectively, presenting an improvement of more than three quarters of a point; however, no information after 2005 is available at a local level. According to information obtained by the database of the World Bank, the Gini index for Mexico from 2000 to 2006 decreased from 0,5308 to 0,5007 and then increased again to 0,5174 in 2008. Both at a national and local level, the level of inequity was reduced from 2000 to 2005; then, assuming that the behaviour showed by Mexico can be interpolated to Guadalajara, I generated the data from 2006 to 2009 using a linear function having the same increasing rate as the one presented by Mexico from 2006 to 2008. Figure 4.26 shows the change of inequity in Guadalajara from the period of 2000 to 2009.

As a matter of comparison, the Gini index of Berlin from 2005 to 2008 remained unchanged on 0.3, and according with the UN the lowest Gini index registered is 0.25. Even though, Guadalajara reduced the level of inequality by 0.0756 points in the Gini index scale from 2000 to 2005, the level of inequity barely increased in 0,009 from 2005 to 2009; Guadalajara is still considered one of the most unequal cities in the world according to the State of the World's Cities Report (2010/11) (UN-HABITAT 2012). During the survey implemented by the author in 2008, this level of inequality was observed; while in some of the richest neighbourhoods in Guadalajara, it is easy to find houses that exceed millions of USD and have an area over 2500 m^2, in other regions of the city, houses of barely 20 m^2 and lacking water and drainage systems were observed. Unfortunately, this situation is not exclusive to Guadalajara, the same phenomenon occurs throughout the whole country. A clear example of this is while the percentage of population in Mexico living in patrimonial poverty was 47 %, the richest man in world nowadays is Mexican.

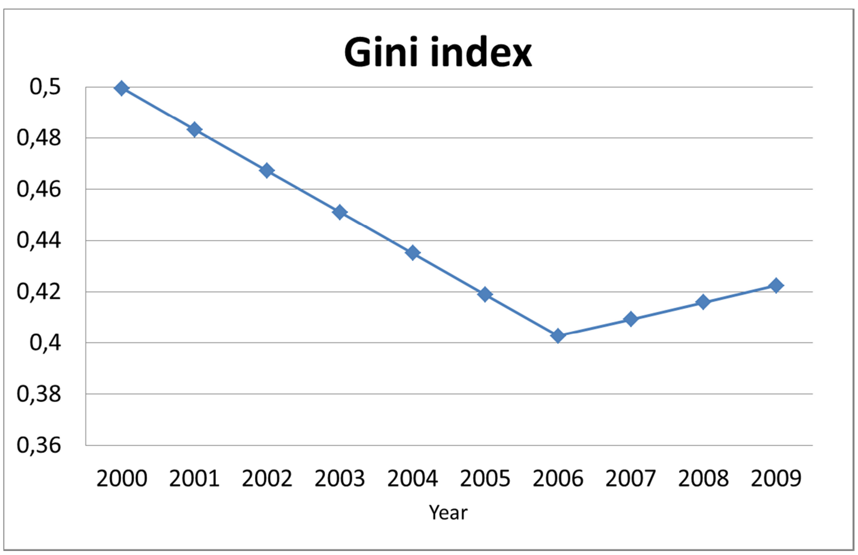

Figure 4.26: Gini index Guadalajara 2000-2009 (author's elaboration)

Patrimonial poverty.

In the table "Evolution of income poverty in Mexico" presented by CONEVAL in the file "Anexo estadístico pobreza por ingresos.xls," the behaviour of urban income poverty at a national scale from 2000 to 2010 presents a practically constant decrease of poverty from 2000 to 2006, and then a constant increase until 2010. The same behaviour is seen at a local scale in Guadalajara where the percentage of population living in income poverty decreased from 36.12 % in 2000 to 34.44 % in 2005; also for this variable, no information at a local scale is available after 2005. Assuming again Guadalajara follows the same behaviour of the urban poverty at a national scale, the data from 2006 to 2009 were generated using a linear function with the same gradient as the function that represents the poverty increase at a national scale. The trend of poverty change in Guadalajara is presented in figure 4.27.

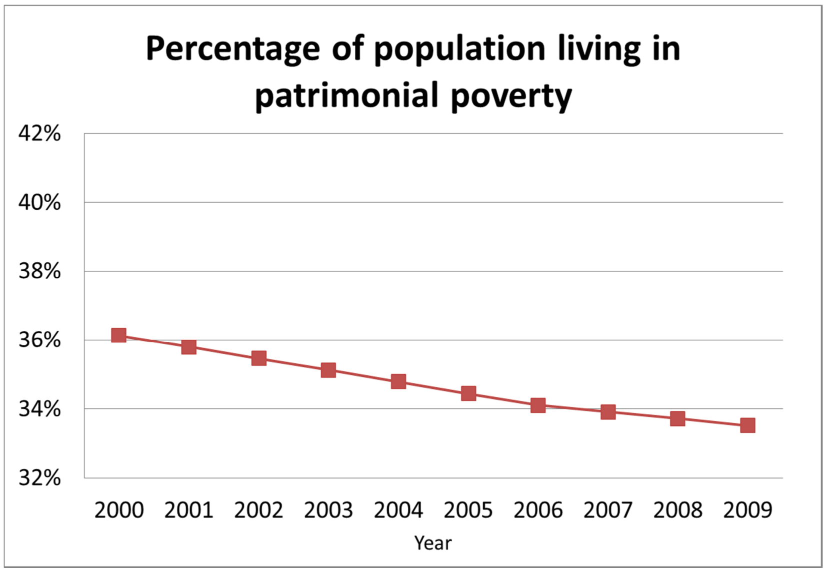

Figure 4.27: Percentage of population in Guadalajara living in patrimonial poverty 2000-2009 (author's elaboration)

GDP per capita.

GDP per capita in Guadalajara showed a variation from approximately 7600 USD to 8800 USD (figure 4.28) between 2000 to 2008; however, in 2009 the GDP per capita dropped to 6390 USD. This drastic change can be explained by the economic crisis suffered worldwide in 2009. Moreover, in Mexico, this crisis was more pronounced due to two important factors, the AH1N1 virus epidemic which started in Mexico (which later was declared as the first pandemic of the 21st century), and the war against the drug cartels started by President Calderón in 2007. Nonetheless, as was predicted by experts from the Mexican Bank, the economy was reactivated in 2010 and this was reflected in an increase in the national GDP per capita of 9.5% from 2009 to 2012. The same improvement in the local economy can be observed in Guadalajara, where the GDP per capita increased from 6390 USD to 6994 USD from 2009 to 2010, representing an increase of 9.46%.

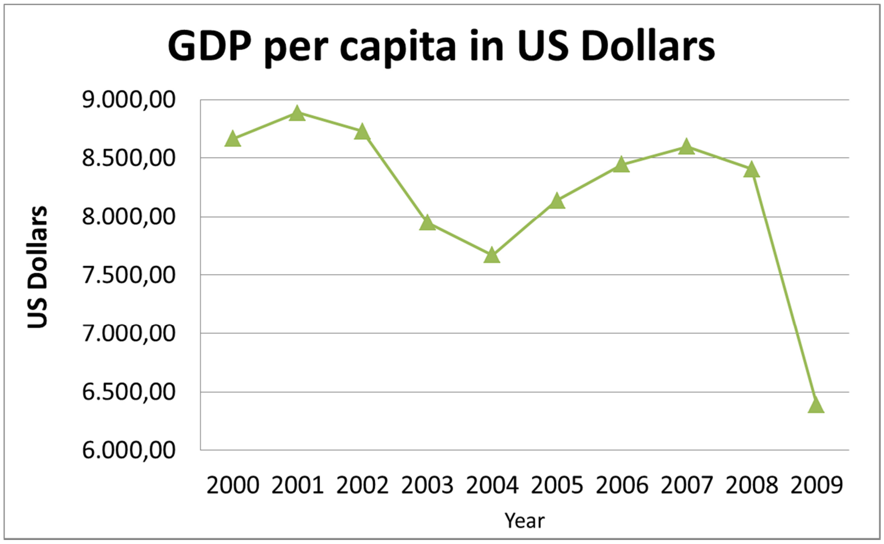

Figure 4.28: GDP per capita in Guadalajara 2000-2009 (author's elaboration with data from SEIJAL: http://sieg.gob.mx/general.php?id=2&idg=168)

Figure 4.29 shows how these three indicators interact in Guadalajara; No strong correlation between the three indicators was observed. GDP per capita and the Gini index had a correlation Pearson's coefficient of 0,582 with a significance of 0,078, while GDP per capita and patrimonial poverty had a Pearson's coefficient of -0,692 with a significance of 0,027. On the other hand, the Gini index and patrimonial poverty had a Pearson's coefficient of -0,102 with a significance of 0,779. Although GDP per capita decreased considerably in 2009, in the normalization procedure, this decrease was not so notorious because the maximum and minimum GDP per capita in the world also changed. Based on this, Guadalajara must reduce its poverty level, drastically increase the equality in the income distribution and develop more its economy to be considered socio-economically sustainable; however, the trends show Guadalajara is headed in the right direction.

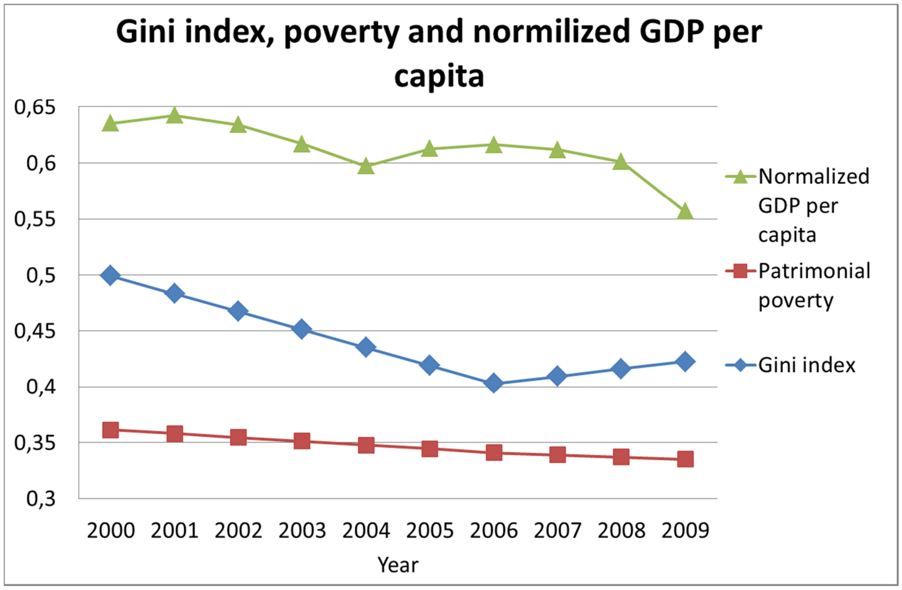

Figure 4.29: Comparison of Gini index, percentage of population living in patrimonial poverty and normalized GDP per capita of Guadalajara 2000-2009 (author's elaboration)

4.2.2.6 Water company income/expenses balance

In figure 4.30 the income/expenses comparison is presented. In the early years of the last decade, SIAPA showed a positive trend regarding earnings obtained each year (with the exception of 2005); however, from 2008 a large reduction in the earnings was observed, resulting in losses in 2009 and 2010, presenting a negative trend on those years (figure 4.31).

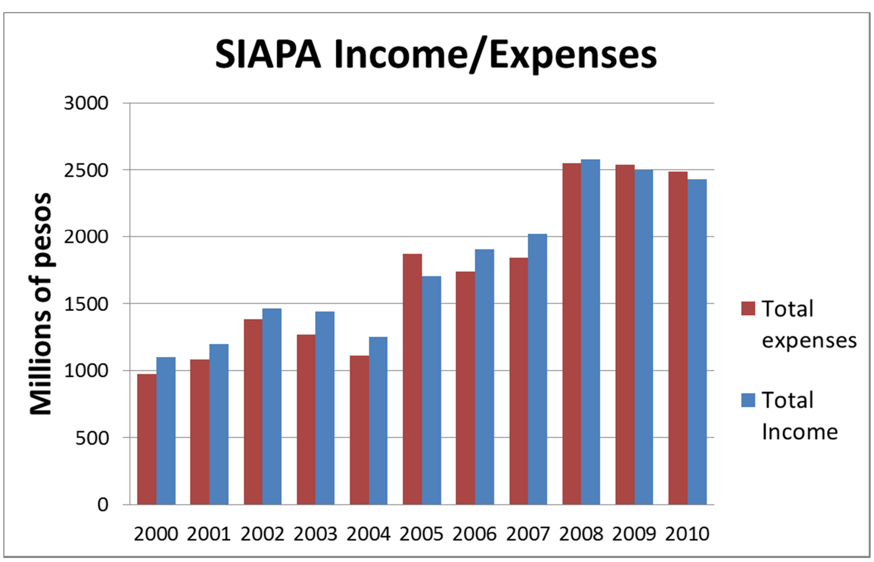

Figure 4.30: Relationship between income and expenses of SIAPA years 2000 to 2010 (author's elaboration with data from SIAPA: www.siapa.gob.mx/transparencia/los-estados-financieros-mensuales)

This situation can be explained by the worldwide economic crisis which affected Mexico severely because it was combined with the AH1N1 pandemic and the war against drug cartels. Looking in detail to at Income/Expense reports from SIAPA, there is a strong negative correlation between operational expenses and the earnings or losses reported by SIAPA. In the years with losses reported (2005, 2009 and 2010) a big amount of operational expenses was reported; even in 2008, when the earnings diminished drastically, the operational expenses were also high.

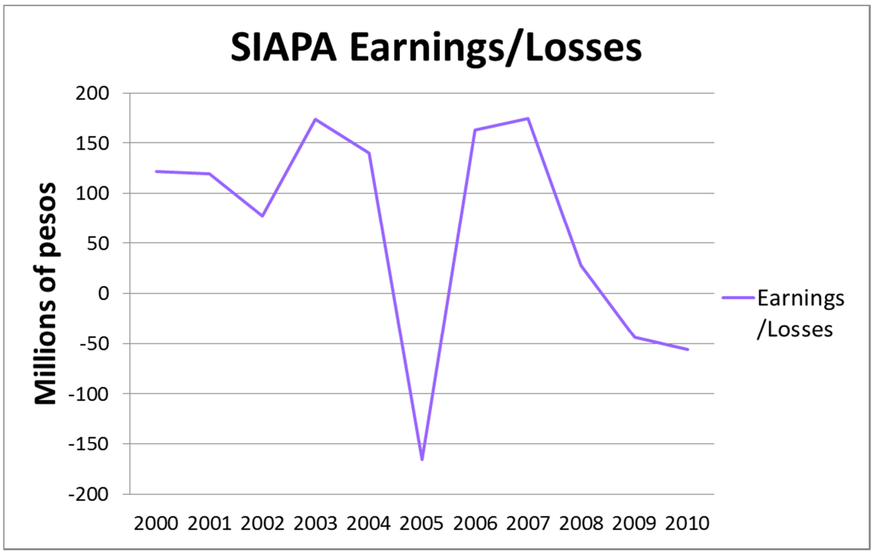

Figure 4.31: Earnings/losses of SIAPA in millions of pesos (author's elaboration with data from SIAPA: www.siapa.gob.mx/transparencia/los-estados-financieros-mensuales)

During the years in which losses were reported, it is supposed that some part of the water distribution was subsidized; this situation can also be seen in the number of refunds and discounts in these years, which were constantly increased.

One of the main objectives of the NWL was to make the urban water supply entities financially self-sufficient. Basic economic theory states that the price of a service should be at least as high as the cost of the service itself (Rogers, et al. 2002). In order to reach that goal, water companies must obtain their income from the users and should not receive any governmental subsides. However, without proper water pricing, this goal is unlikely to be reached. On the other hand, access to water is internationally considered a human right, therefore, is amoral to charge for the amount of water which is essential for survival purposes (20 lts per person per day according to the WHO).

In the case of the city of Guadalajara, the prices charged by SIAPA in every fiscal year are determined by the congress of Jalisco and published in the Revenue Law of the Municipality of Guadalajara (La ley de ingresos del Municipio de Guadalajara 2010). Figure 4.32 presents the relationship between the amount of water consumed per month in cubic meters and the related monthly payment for the water consumed. On first sight, the curve obtained (exponential curve) is as expected, at the moment the consumption is increased linearly, the total amount to pay increases exponentially; in other words, it seems that the big water consumers are being punished by paying much more than the small consumers, , apparently promoting reduction of water consumption.

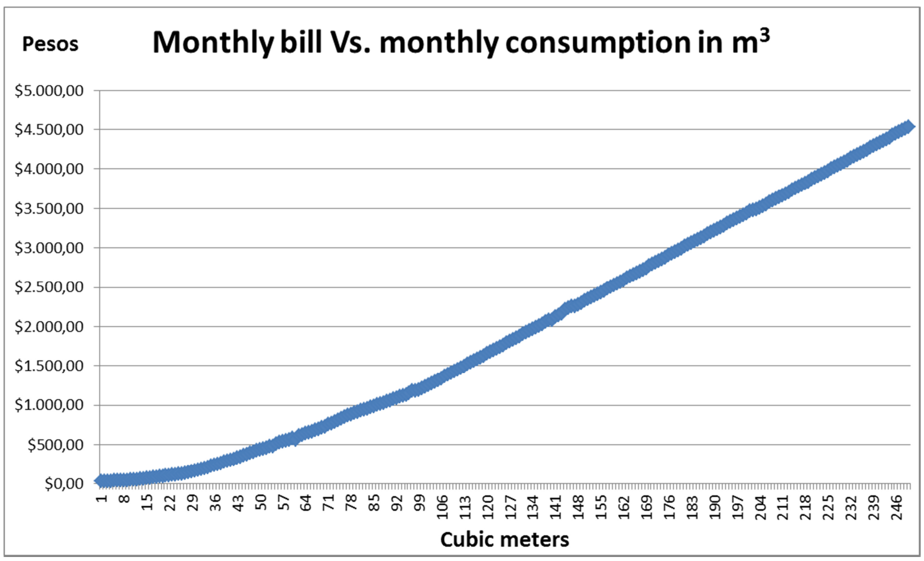

Figure 4.32: Water consumption in a month Vs. total amount billed for the water consumed

However, if we look at the price per cubic meter related to the total amount of water consumed, the truth appears (figure 4.33). If we observe the curve presented in figure 4.33 after starting with a peak of 31 pesos per cubic meter, the price gets reduced following an inverse function ($Y(x) = 3.09+26.6/x$) until reaching a stable region near 4.9 pesos per cubic meter, starting to increase logarithmically ($Y(x) = -15.35+6.11\ln(x)$) with the consumption of 25 m^3 per month. In this case, for example, a family (four members) which consumes less water, even only for their basic needs, pays between 50 and 520 percent more per cubic meter than a family which consumes between 90 and 200 litres per person per day (between this range, the price per cubic meter remains at 4.9 pesos). This tariff scheme is not designed to absorb the costs of delivering water for basic needs by users who consume more, but to punish users who consume less.

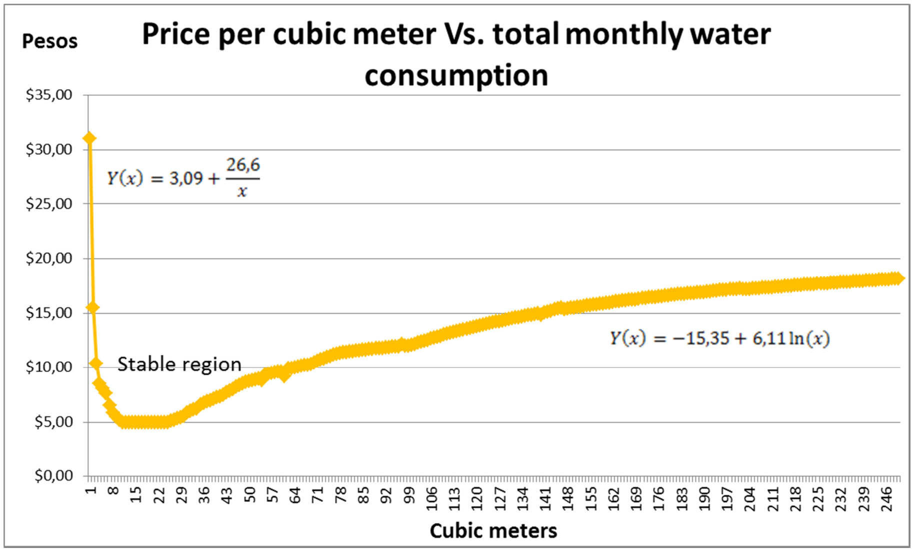

Figure 4.33: Price per cubic meter according to total water consumed in a month

A good tariff scheme should be designed to cover the production cost (the cost of extracting, treating and distributing water), administrative costs and environmental costs (wastewater treatment); however this scheme should be socially responsible: a base amount of water, enough to cover basic needs, should be distributed without any cost to all users. But the question arises, who will pay for these 20 litres mentioned before? The answer suggested by the author is: all users by themselves.

There are, basically, three different tariff models: The first one is the called fixed tariff, where the water bill remains constant independent from the amount of water consumed. Normally this tariff is calculated based on the size of the house, the number of water intakes or the number of members of the household. The second one is the variable tariff, when the water bill is charged accordingly to the amount of water consumed in the month; in this model, the bill can have a continuous variation or may change in steps. The third one is a combination of both models, a fixed part which is charged normally to cover administrative expenses, or as in the case of the city of Guadalajara, to cover handling of waste water; and a variable model, to cover the expenses of the water supply. The tariff suggested here is a combined variable tariff with a small fixed element which will cover the administrative costs of the bill. The model should have a variable element which increases the price per cubic meter according to each meter consumed; this element should be described by a quadratic function. The second element is designed to cover the wastewater treatment cost; this element should follow a linear function multiplied by a factor less than 1, and the reason for this is because the wastewater produced is always less than the water supplied. In other words, the model suggested is a second grade function (equation 4.1):

$$P(x) = \begin{cases} Ax^2 + Bx + C, & x > M * 0.6 \\ Bx + C, & x \leq M * 0.6 \end{cases} \tag{4.1}$$

Where *x* is the amount of water consumed in a month, *0.6* is the amount of water needed to satisfy basic needs in a month, *M* is the average number of family members in a specific year, *A* is a constant which will adjust how fast the increase will be, *B* is a constant to determine how much wastewater was treated; and *C* determines the administrative costs of billing; constants *A*, *B* and *C* should be determined by the water company.

The reason for having a quadratic increase in the water bill is to promote water savings, charging considerably more for high consumption and less for low consumption. Under this scheme people who save water are not punished with high prices. Also within this model, the amount of water needed to accomplish basic needs is supplied without any cost to all users, and only after this amount is consumed the user will start to be charged. In the case of a poor family with more members than the average, or several poor families consuming water from the same connection, special subsides granted by the government can be applied, but independently from the water bill (following the subsides scheme used in Chile).

Another modification here, compared with the actual scheme, is that wastewater treatment is billed according to the amount of wastewater produced and not as a fixed tariff as is stipulated today.

4.2.2.7 Percentage of water loss in the distribution system vs. total water extracted

Like several major cities in Mexico, Guadalajara has a significant problem with water loss in the distribution system. For example, Mexico City has a water loss level of 40 % which is caused, mainly, by fractures in or the age of the pipes (Izazola et al. 2001).

In figure 4.34, the percentage of water loss in Guadalajara is presented. The water loss, from the moment it is extracted until is delivered to the final user, ranges between 35.4 % and 38 %, with an average of 36.81 %. This high level of water loss can be partially explained by the actual state of the pipes. According to the activities report of SIAPA for 2009, the water distribution system in Guadalajara has 7685.7 km of pipelines; of which approximately 45 % are more than 30 years old (figure 4.35).

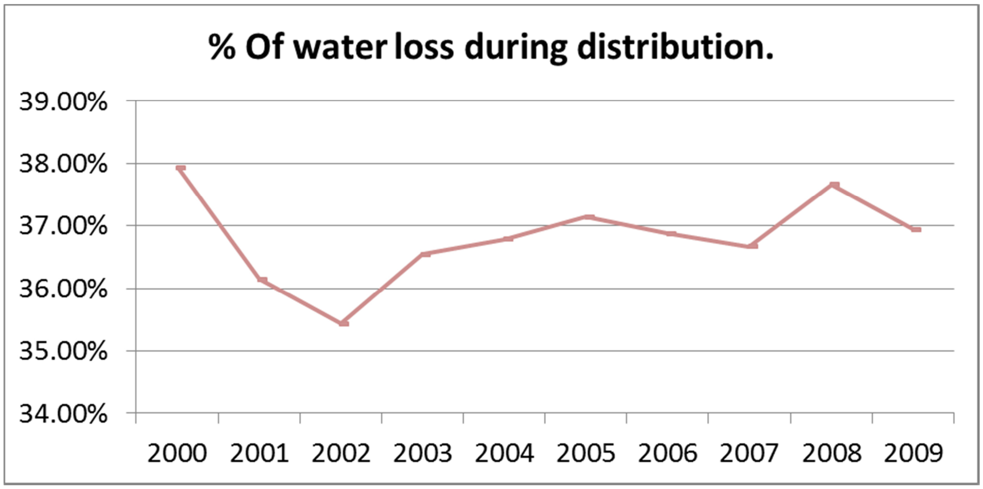

Figure 4.34: Percentage of water loss in the distribution system in Guadalajara (author's elaboration with data from SIAPA: SIAPA 2010A, www.siapa.gob.mx/sites/default/files/informe_2009.pdf)

Just a small percentage of the pipelines are relatively new; only 25.5 % of the pipelines are 20 years old or less. According to information provided by SIAPA, the useful life of a pipeline varies from 20 to 60 years depending of the material from which it is made (table 4.4).

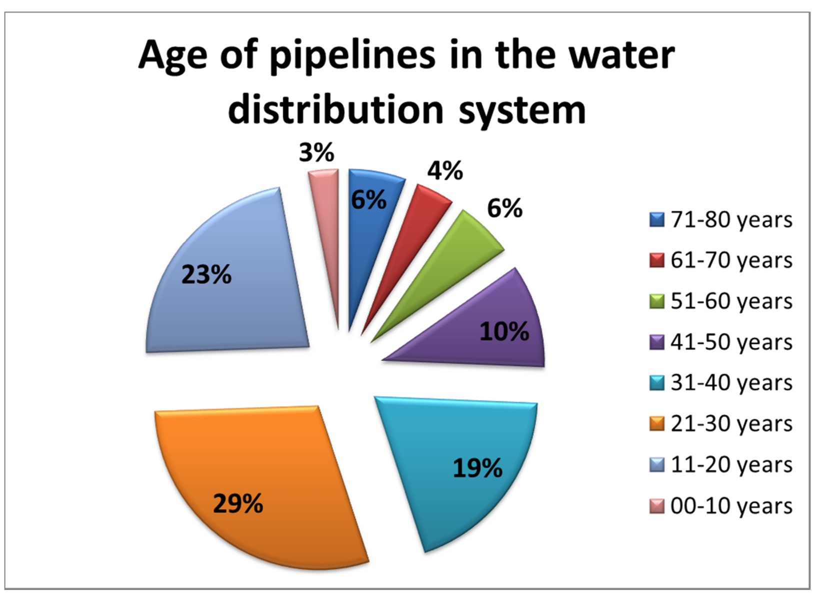

Figure 4.35: Distribution of the age of the pipelines of the water supply system of Guadalajara (source: SIAPA 2011B)

70 percent of the pipelines that form the water distribution system are made from asbestos-cement and 14 percent from PVC; both have a maximum useful life of 30 years. Unfortunately there is no direct information about the relation between the pipelines segments and their age, but by making a simple correlation between pipeline material and the age of the distribution network one can easily see that, in the best case scenario, 30 percent of the distribution system must be replaced and in the worst case 45 percent, far away from the estimates made by SIAPA in which they stated that only 25 percent of the pipelines need to be replaced.

Table 4.4: Relation between pipelines' material and useful life (SIAPA 2011A)

Pipelines' material	Useful life
Asbestos-Cement	Between 20 and 30 years
PVC	Between 20 and 30 years
High density polyethylene	Between 30 and 50 years
Reinforced concrete	Between 30 and 50 years
Steel	Between 40 and 60 years

The situation explained above is clearly exemplified with the following information: in 2009, 1.45 km of new pipelines were installed, and 5.3 km of old pipelines were replaced after they exceed their useful life; this 5.3 km represents only 0.07 % of the total network. From 2000 to 2009, the repairs in the pipelines due to leakages ranged between 2511 in 2006 and 3688 in 2001, with 2993 repairs in 2009. On the other hand, repairs to the water connection to the water distribution system ranged from 13047 in 2004 to 10207 in 2009

In spite of the critical situation of the pipelines in Guadalajara, one of the main problems of replacing pipelines is the high cost and immediate disturbance for citizens (streets closed for long periods of time, building works, noise, etc.); the benefits of replacing old pipelines are not visible like a monumental infrastructure project such as a water dam or a bridge; therefore, politicians do not want to take the risk of disturbing the citizens because it may cause a negative impact to their electoral aspirations (even though, in Mexico re-election for the same public position is not allowed; the politicians always look to relocate their selves in a new public position). Adding to this, the lack of a management continuity in SIAPA (including, obviously, the director of the company) makes it hard for actions of this magnitude to be implemented.

4.2.2.8 Percentage of water treated of total wastewater produced

SIAPA has two wastewater treatment plants in operation, Rio Blanco (with a treatment installed capacity of 150 L/s) and Virreyes (with a treatment installed capacity of 12 L/s).The wastewater treatment plant Rio Blanco started operation in 2001, however only data since 2002 is available; on the other hand the wastewater treatment plant of Virreyes began its activities in 2006.

Figure 4.36 shows the percentage of wastewater produced that is treated; the results are deplorable. For example, the maximum percentage of treated wastewater was in 2005, at barely 1.56 % of total wastewater produced in that year. This means that basically all wastewater produced in Guadalajara is delivered to a natural basin, in this case the Santiago River, without any treatment; the health and ecological impacts that fact represents are enormous. This situation can be seen in Santiago River nowadays; the river has received domestic and industrial wastewater from MZG for more than 30 years. The analysis made of the water of the Santiago river shows evidence of toxic discharges, such as heavy metals hydrocarbons, benzenes, detergents volatile organic compounds and microorganisms, among others, from the industrial parks near the river or the Ahogado channel (Duran et al. 2009).

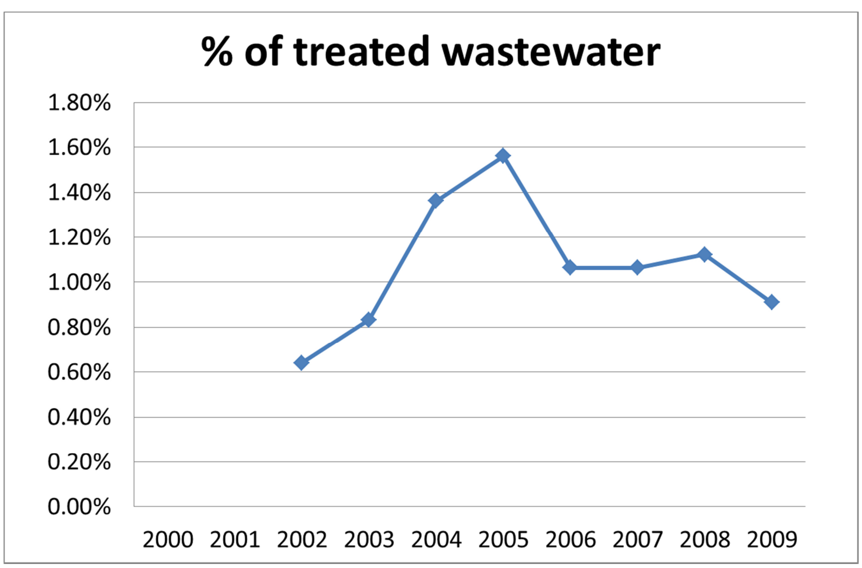

Figure 4.36: Percentage of wastewater produced that is treated in Guadalajara (source: SIAPA 2010B)

One of the best strategies a city can implement if it is suffering from water scarcity is to reuse a large amount of the treated wastewater; in this way water extraction can be reduced. In Guadalajara, this issue has significant relevance due to the fact that 54 % of the water consumed in the city comes from Lake Chapala. The more Guadalajara reuses the treated wastewater, the less water needs to be extracted from Lake Chapala. Figure 4.37 shows that treated wastewater was started to be reused (mainly for watering green areas) in a low proportion in 2005, increasing this percentage drastically in the following years; the rest of the treated wastewater is delivered to the natural basin. However, as we saw in Figure 4.36, just a small percentage of the wastewater produced is treated, so the 17.5 % of reused treated wastewater in 2009 only represents 12.4 L/s, basically only the full operational capacity of Virreyes wastewater treatment plant.

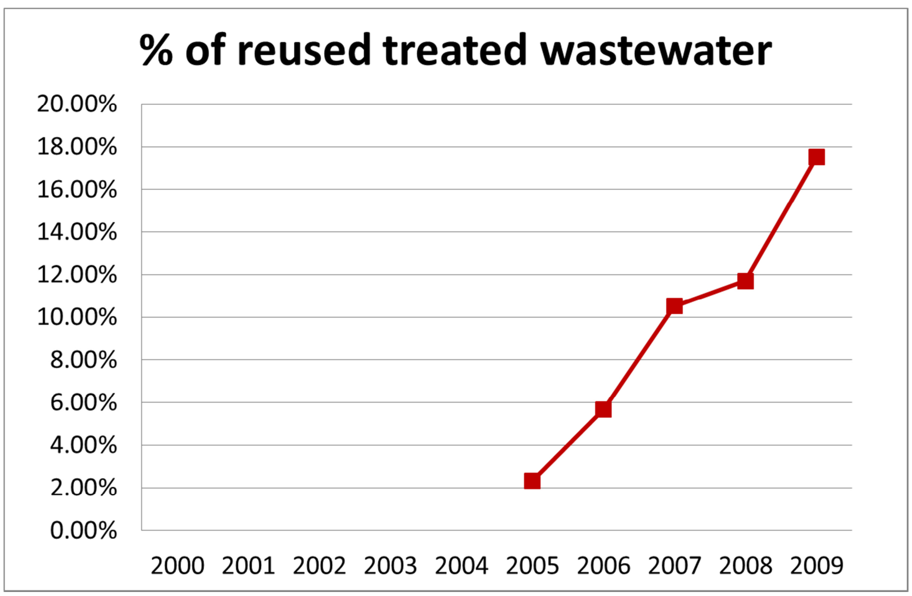

Figure 4.37: Percentage of treated wastewater that is reused in Guadalajara (source: SIAPA 2010B)

4.3 Guadalajara and Berlin, a comparison between two cities of different performance

In Chapter 2, it was argued the reason for selecting the geometric mean as an aggregation method for the water sustainability index was that the selected indicators are naturally bounded by zero. The geometric mean also has the big advantage of avoiding the possibility of eclipsing a bad performance of one the indicators by the good performance of the rest; for that reason, the index final result is more sensitive to low performance indicators than the arithmetic mean. In order to evidence this situation, the sustainability of domestic of water supply in Guadalajara was compared with the results obtained from Berlin.

But why Berlin? Berlin is considered a role model regarding water management because of different factors, such as the excellent water quality level, the low water consumption even though water availability is considerably high, and the extremely low water loss during distribution. For all these reasons, among others, Berlin was selected a target sample to show the model behaviour of a case with good performance. The evaluation period selected was between the years 2002 and 2009.The reason for shortening the original evaluation period is because the lack of information of one variable for Berlin in 2001. The comparison results are presented in figure 4.38.

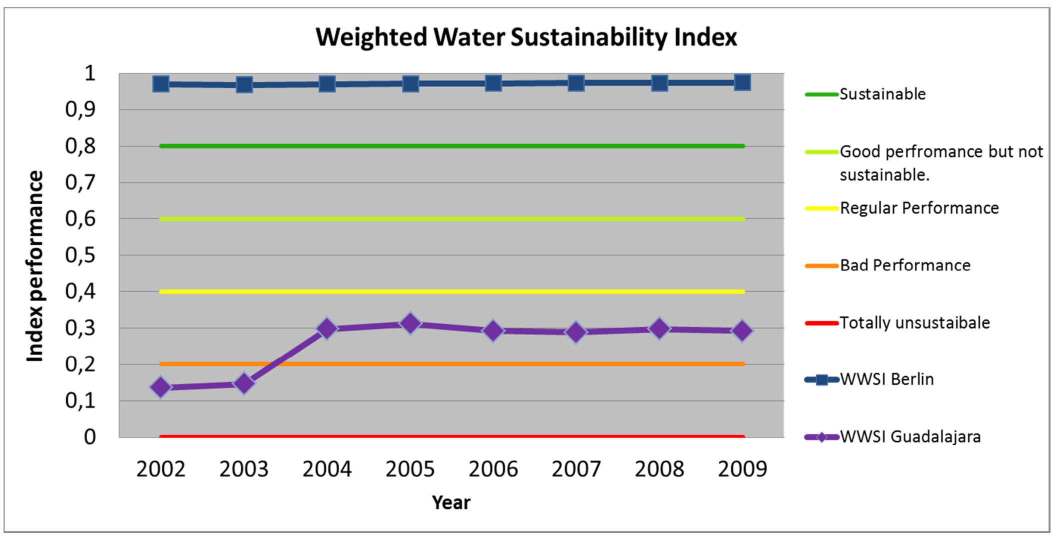

Figure 4.38: Comparison between Guadalajara and Berlin performance in sustainable water supply

As was expected, the result obtained from evaluating Berlin with the weighted WSI (WWSI) was almost perfect. Almost all the years had an overall result over 0.97; only in 2003 was the result obtained slightly lower, with a result of 0.9687. The specific results for each indicator are presented in figure 4.39.

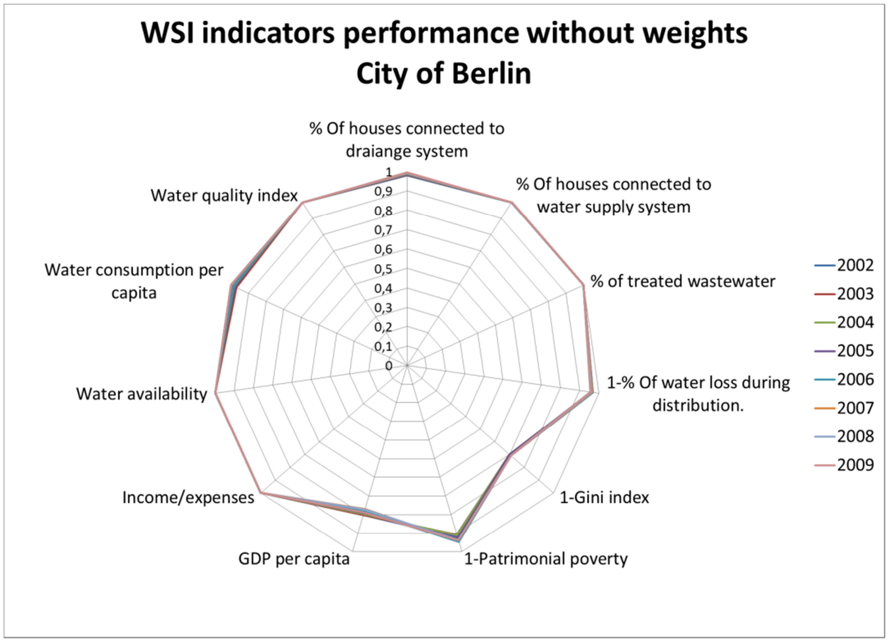

Figure 4.39: Indicators' performance without weights for the city of Berlin, evaluation period year 2002 to 2009

Basically, there were only two indicators where Berlin presented a performance between regular and good; the Gini index and GDP per capita, as these two variables have the lowest weighting, they did not considerably affect the final index result.

As can be seen in the comparison of both cases, in the case that one indicator has an extremely bad result, the final result of the index is affected drastically.

As was already exposed, the overall bad performance in Guadalajara was caused by the unsustainability of two indicators, water availability and percentage of wastewater treated. As soon as the new two wastewater treatment plants, El Ahogado and Agua Prieta, start to work at full capacity, separate collectors are implemented for separately collecting rain water from gray/wastewater, and the government starts to implement measures to improve the recharge rates of the Toluquilla and Atemajac aquifers, the final result of the index will increase drastically.

4.4 Future scenarios for Guadalajara

As was presented previously, Guadalajara presently is not sustainable in the supply and use of water; however, a positive trend was observed during the last decade; nevertheless, the variability of driving forces may influence water supply for Guadalajara in the future – both in negative and positive ways. For that reason, there is a need to determine future scenarios. Since it is not possible to do a proper estimation of all variables of this model, some of them have been used to develop three distinct scenarios: worst case, expected case and best case, in order to determine the necessary strategies Guadalajara must follow.

In order to develop the future scenarios, first the scenarios for the independent variables will be presented, and afterwards the index for each scenario will be built.

4.4.1 Water availability

One of the main concerns in Guadalajara was, is and certainly will be water availability to meet water demand. Therefore, determining water availability in the main water supply sources of Guadalajara will be a key issue for proper water management in Guadalajara.

As was mentioned before, Lake Chapala is the main water source for the city supplying 55 % of the total water consumed today. Because Lake Chapala is a shallow lake, even with its large extension, its water level is considerably affected by droughts and high amount water extraction rates. Therefore, the Mexican Water Technology Institute (IMTA), generating 50 synthetic series based on the information on historical average precipitation from the years 1947 to 1998, elaborated a prognosis for the water level up to 2030. Figure 4.40 shows the water storage of Lake Chapala on the 1st of June (before the rainy season starts) for the years 2012 to 2030.

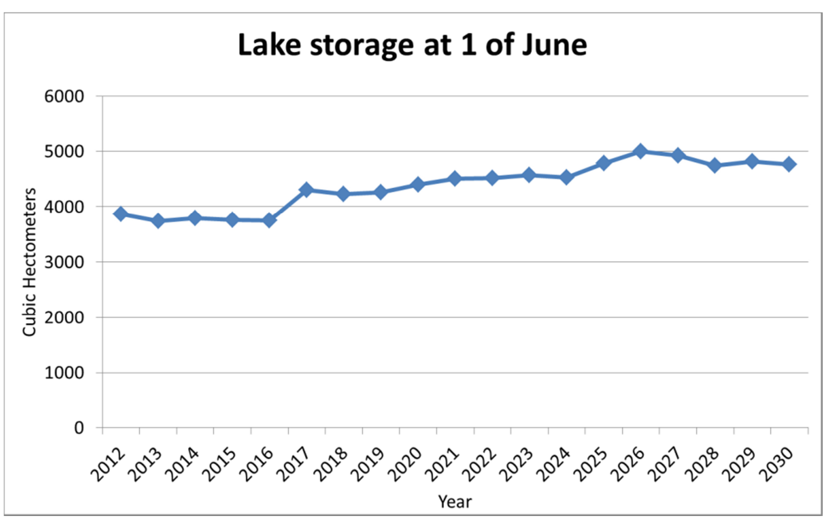

Figure 4.40: Lake storage in cubic hectometres at first of June for the period 2012-2030 (source: CONAGUA 2010B)

The average storage volumes presented in the last figure represents the 50th percentile of the results obtained after the analysis was performed. Figure 4.41 shows the best, expected and worst scenarios for Lake Chapala in the next 20 years; the information presented is based on the 90th, 50th, and 10th percentiles representing the best, expected and worst case scenarios.

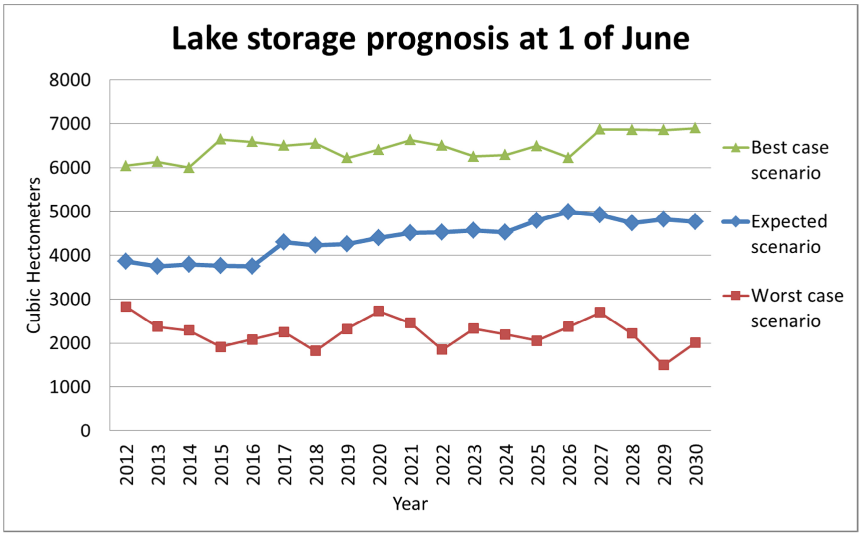

Figure 4.41: Lake storage prognosis: best case, expected and worst case scenarios (Source: CONAGUA 2010B)

As can be easily observed in the last chart, only the in the worst case scenario, is the storage of Lake Chapala in low water level periods expected to decrease under the minimum permissible storage limit of 2000 hm^3 on four occasions.

However, as we saw in the behaviour of the lake during the last years of the 1990s and the first of the 2000's, when a long period of droughts occurs, the volume can be reduced drastically. Nowadays (year 2012) a severe drought is affecting the state of Jalisco and the actual volume of Lake Chapala is 3850 hm^3; as the rainy season starts around the end of June, it is expected that the volume will decrease more before it increases with the rain. In the case of a severe rainy season, the lake volume can fall to less at the end of the year than it was at the beginning (as occurred in 2011 when the lake lost a net volume of 1430 hm^3, representing a 23 % loss). The other main water sources for the city of Guadalajara are the Aquifers under the city. Currently, the Atemajac aquifer, which supplies 40 % of the water consumed, is overexploited, having an availability after extraction of -1.41 hm^3 per year. In the area of Cajititlan, southwest of Guadalajara, there is another aquifer that supplies the municipality of Tlajomulco de Zuñiga. This aquifer could be considered an option for water supply due to the availability of 10.7 hm^3 per year after actual extraction rate; however this availability only represents 0.34 m^3/sec, much less than the 2,7m^3/sec that are extracted by SIAPA from Atemajac aquifer.

The information previously presented shows that, without other water supply projects, Guadalajara will still be dependent on Lake Chapala for its water supply, so if the volume of the lake decreases drastically as happened from 1999 to 2003, water extraction from the lake will endanger the lake's survival.

Water availability situation can be worsened by the fact that the Atemajac aquifer is already overexploited, at risk of suffering salinization, and being no longer suitable for human consumption. On the other hand, if a series of water dams are built to accomplish Guadalajara's demand, as it was intended with Arcediano or Rio Verde dams projects, the local environment where the dams could be located would be affected, representing the loss of local biodiversity (as would have happened with the Arcediano dam) or local communities.

Therefore, in all possible scenarios, the future of Guadalajara's water availability is uncertain. Several possible solutions have been already suggested by different authors. One possible solution suggested by Gleason (Gleason et al. 2011), is to take advantage of the rain precipitation over Guadalajara. The average yearly rain precipitation over the city of Guadalajara (from 1958 to 2001), according to CONAGUA, is 535.5 hm^3, which represents 17 m^3/sec; if just 50 % of the total precipitation during the year can be infiltrated into the subsoil, or reused, that will represent 8.5 m^3/sec water availability which is the actual water supply by SIAPA. In a city with an imperviousness of between 75 to 100 %, to try to recover water from rainfalls is a big challenge; several infiltration wells should be located over the city, and it is also possible to implement sewage systems with infiltration systems included, as was successfully implemented in Tokyo in the 1980s (Furuami, et al. 2008). Another possibility is rain harvesting at a household level; harvesting systems can be implemented over the roofs to catch rainwater, this water then is conducted to small reservoirs for a later usage. The main disadvantages of this technique are that the water reservoirs use a considerable amount of space, and the first runoff of water from the roof usually washes all pollutants that have settled prior the rain. Therefore, a system which can separate and send to drainage the water of the first rains and then the rest to the water reservoir should be constructed. In the case of Guadalajara, where 50.33 % of houses have a water cistern, the possibility of using the cistern as water reservoir exists, it would be just a question of connecting it directly to the harvesting system, and adding a pass key system between the public water supply system and the cistern.

Another option Guadalajara has to reduce water extraction from both Lake Chapala and the Atemajac aquifer, is to use the water from springs; nowadays, the water from 30 springs in the city are not being utilized, and their water is being exposed to pollutants or is poured into the sewage system. As an example, the Colomos Spring produces enough water to supply 75000 inhabitants (150 l/day per person), and its water is being discharged directly to Patria canal and later reaches the Atemajac river which is highly polluted with discharges from the city (Gleason et al. 2011).

Finally, part of the treated wastewater could be reutilized for activities where non-high quality water is required, such as for cleaning purposes or for watering green areas. As was mentioned before in this chapter, an average of 1.08 % of total wastewater produced in Guadalajara is being treated, and from this 1.08 % only 17.5 % is being reused. However, with the start of operation of two new wastewater treatment plants, is expected that 100 % of the wastewater produced (in the dry season) will be treated; if only the same 17.5 % of treated wastewater is reused, that will mean a savings of 1.35 m^3/sec.

In conclusion, if the water supply strategies in Guadalajara remain as they are today, the city will face several difficulties in water availability. Therefore drastic changes must be made, from radical infrastructure improvements, which will represent high economic investments; to the acceptance of the final user to implement water harvesting systems in their homes. However, even with the execution of all these actions, water availability may remain a big issue for the city due to the continuously growing population and urbanization growth, increasing water demand and decreasing infiltration areas respectively.

4.4.2 Percentage of population connected to water supply system and percentage of population connected to drainage system

The connectivity to water supply and sewage systems in Guadalajara has continuously increased over the last few decades, and is expected to continue on this path for the next few years. In order to build a prognosis for both variables, two logarithmic functions using the data from 2000 to 2010 were generated to determine the connectivity rate from 2011 to 2030. Both trends are presented in figure 4.42.

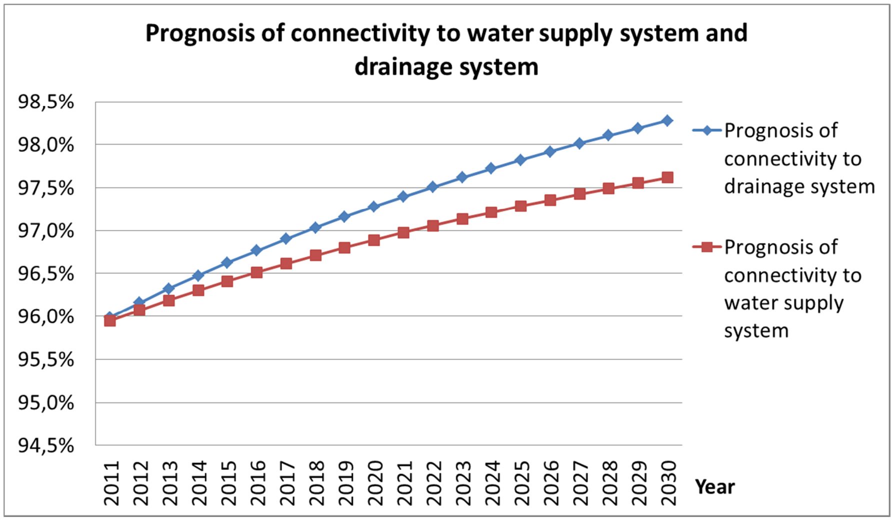

Figure 4.42: Water supply and drainage connectivity prognosis years 2011-2030

Equation 4.2 was used to calculate the number of houses connected to the drainage system and equation 4.3 was used to calculate the number of houses connected to the water supply system.

$$HD(x) = -3.99*10^8 + (52645583.7*ln(x)) \quad (4.2)$$

Where HD(x) is the function of number of houses connected to the drainage system, and x is the respective year.

$$HW(x) = -3.91*10^8 + (51591832.95 ln(x)) \quad (4.3)$$

Where HW(x) is the function of number of houses connected to the water supply system, and x is the respective year.

This prognosis is expected to be real if the variables behave in the same way they did in the last 10 years. However, several factors may affect these two variables in the future; it will depend on the urbanization strategies of the government of the 8 municipalities that constitute the urban zone of Guadalajara. If illegal settlements increase in number, it will be directly reflected by a decrease in both variables. On the other hand, not only should houses be connected to both the water supply and drainage systems, but new segments of both systems should be properly planned to avoid problems like lack of pressure in the water supply or flooding (as has already happened in the new urbanizations near El Ahogado canal).

4.4.3 Gini Index, Percentage of population living in patrimonial poverty and Gross Domestic Product per capita

Due to the lack of long term historical data on the GDP per capita of the state of Jalisco, and therefore of Guadalajara, the possible scenarios of GDP per capita for Guadalajara in the next two decades were based on the historical GDP per capita of Mexico. Figure 4.43 shows the GDP per capita in 2005 USD prices of Mexico for the period of 1970 to 2009.

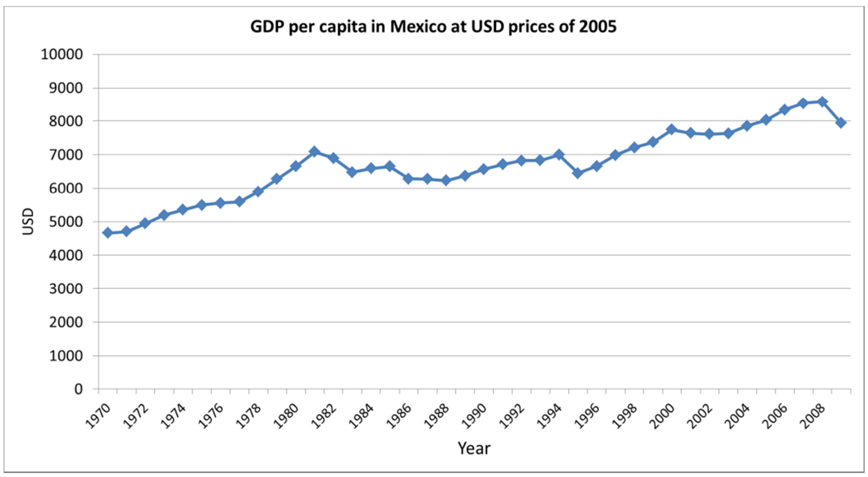

Figure 4.43: GDP per capita in Mexico at 2005 prices in USD (Source: World Bank, http://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD)

From 1970 to 2009, Mexico suffered several crisis reflected by a decreasing of GDP per capita; and most of them were related to the end of the presidential period, and following strong devaluations. At the end of the government of Jose Lopez Portillo, the Mexican bank was nationalized, causing flight of capital. During this period the peso was devalued by 866 %. During Miguel de la Madrid's government, the GDP per capita did not practically grow and the peso was devalued by 1443 %. In 1994, a big crisis started after the devaluation of the peso was put on hold during the entire presidency of Carlos Salinas de Gortari, and finally released by Ernesto Zedillo, causing a devaluation of 68.13 % in just one month (at the end of his period the peso was devalued by 173.87 % (source: Banco de Mexico (http://www.banxico.org.mx/graph/test/?s=SF63528,CF373,1&period=Dia&l=es)). Finally, the last big crisis suffered by Mexico was the one caused worldwide by real estate speculation.

After each crisis, a relatively linear growth always occurred; each growth rate (considering a linear function) after each crisis was calculated and an average growth rate was determined.

This average was used to define the scenario for a continued growth of the GDP per capita for Guadalajara if no crises occur again (figure 4.44); this scenario was established as best case scenario. For the expected scenario, a decrease in the GDP per capita of 473.4 USD per year was determined (an average of all decreases that occurred in the past) and after each presidential period this decrease in the GDP was supposed to occur for one year, and again continuing growth for the next five years. It is considered to be a worst case scenario when no economic growth occurs, therefore the difference with the best performance worldwide will increase with every year that passes.

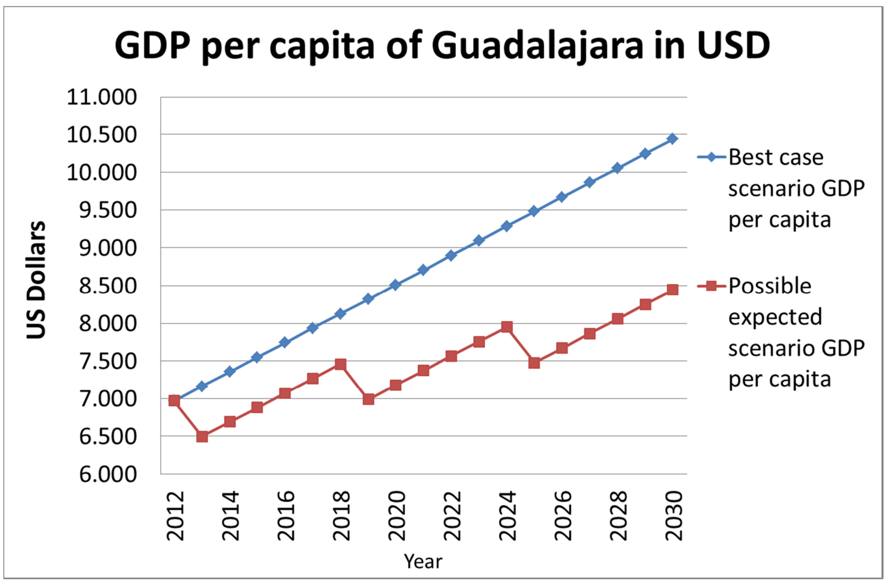

Figure 4.44: Prognosis of GDP Per Capita of Guadalajara in USD

The Gini index and poverty are closely linked with the economic growth of a country; to probe of this statement, a correlation analysis was performed among GDP per capita, the Gini index and the percentage of the population living in poverty with data from 63 countries from the year 2005. A strong correlation between the Gini index and poverty is presented, showing a Pearson's correlation coefficient of 0.784. The same level of inverse correlation was also found between GDP per capita with the Gini Index and poverty respectively (Prearson's correlation coefficients of -0.612 and -0.610). These results demonstrate that with an increase of GDP, a reduction of poverty and inequality occurs.

In the same way, a correlation analysis between the same three variables was performed using data from the OECD countries in 2005. It was found that a strong correlation between the

Gini Index and poverty exists in all member countries of the OECD (Pearson's correlation coefficient of 0.853). The main characteristic of the member countries of the OECD is that most of them are developed countries with a high GDP per capita. In the case of Mexico, a strong inverse correlation between GDP per capita and poverty exists (Pearson's correlation coefficient of -0.613). A correlation between the Gini index and poverty also exists, but is not so strong (Pearson's correlation coefficient of 0.442); no correlation between GDP per capita and the Gini index exists (Pearson's correlation of -0.173). However, if we looked at the results obtained worldwide and also in between OECD members, it is expected that as the GDP per capita in the country increases, a decrease in poverty and inequality will occur. In general terms, the GDP per capita in Mexico has been continuously growing in the last three decades; so, if this correlation remains, there will be a point where the poverty and inequality in Mexico, and therefore in Guadalajara, will be kept low.

4.4.4 Water loss in the distribution system

Over 44 % of the actual supply network has already surpassed its specified lifetime; this may be one of the main reasons for the large amount of water loss during distribution. In order to perform a future scenario of the amount of water lost, it is necessary to determine the state of the network in the future. For that purpose, the number of kilometres of pipelines older than their specified lifetime in 10 and 20 years were calculated. According to the analysis performed, in 10 years over 2200 kilometres will reach their life expectancy, and over 1000 in 20 years, plus the 3400 kilometres that are currently obsolete if no replacement is performed; in other words, there are over 6700 kilometres of pipelines with a high risk of leaking.

Figure 4.45 shows the amount of obsolete pipelines up to 2030 if the replacement rate remains as it is today (2010), with an average replacement rate of 150 kilometres per year and a replacement rate of 340 kilometres per year.

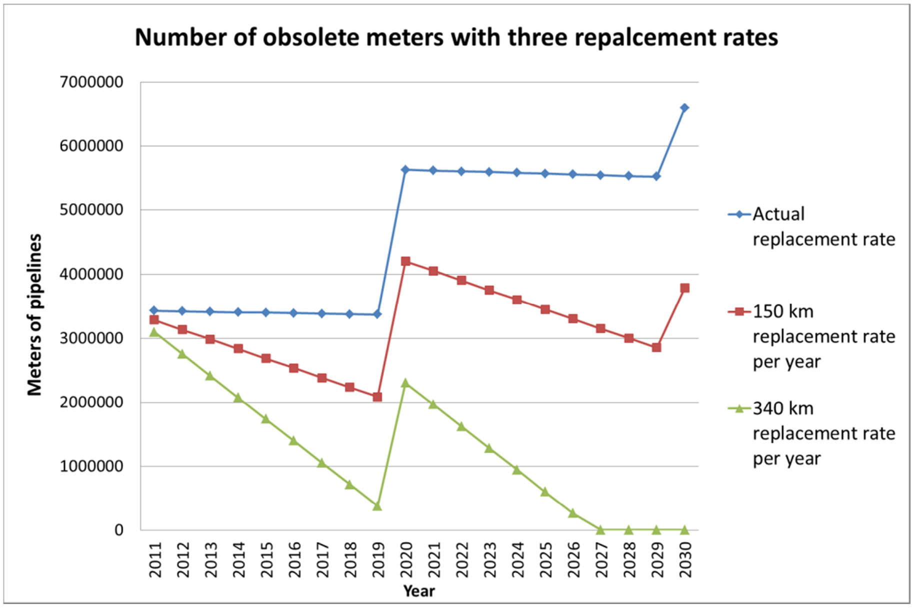

Figure 4.45: Obsolete pipelines (in kilometres) with different replacement rate, years 2011-2030

As is shown in figure 4.45, with the average actual replacement rate of 28 kilometres in the last 6 years (2005-2010), the actual situation is not getting better but worse. If this rate continues, by 2030 over 6500 kilometres of pipelines will be past their lifetime. Currently 34 % of water is lost during distribution, that is with only 3400 kilometres of the pipelines obsolete, this means that the actual replacement rate will worsen, maybe reaching 50 % of water loss. In case of a replacement rate of 150 kilometres per year, by 2030 the situation will remain as it is today, with 3700 kilometres of obsolete pipelines and around 30 or 35 % water loss. Only with a replacement rate of 340 kilometres per year, will the obsolete pipelines will be replaced by 2027, thus reducing water loss up to a maximum of 10 % in the city (actually, a water loss of 0 % is practically impossible to reach) (Corton, et al. 2003).

4.4.5 Water company income/expenses balance

Income-expenses balance changes in SIAPA are caused by several factors, but the main two factors are the amount of money spent on new infrastructure (investments) and the amount of money received from service payments. The main infrastructure investment the water supply system requires today is the replacement of the obsolete pipelines. As was previously mentioned, 340 kilometres of obsolete pipelines must be replaced every year to renew the whole system. Using the transparency law in Mexico, SIAPA was asked how much it costs to replace one kilometre of pipeline, according to the diameter and material of the pipeline, the soil composition and the excavation's depth; however SIAPA answered that this information is reserved because is essential for budget planning. Therefore, one construction company specializing in these installations was consulted. The answer receives was that the cost of installing a meter of plastic CPVC pipeline in Guadalajara (assuming the common soil characteristics) is $ 500 pesos per meter.

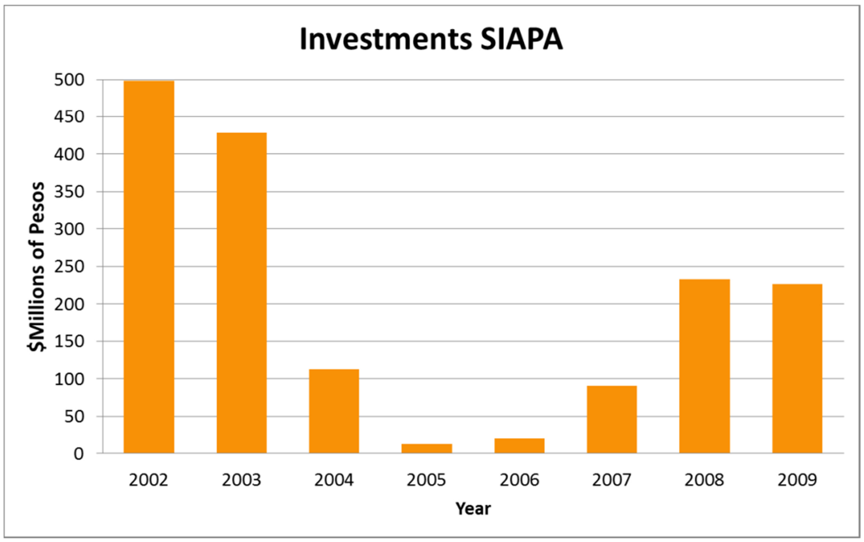

Figure 4.46: Total amount of money invested by SIAPA from year 2002 to 2009 (source: www.siapa.gob.mx/transparencia/los-balances-generales)

In figure 4.46, the amount of money used in investments from year 2002 to 2009 is presented. The average amount of money used in this rubric was 202.9 million pesos. The average of meters replaced and installed new from 2005 to 2010 was 22428 meters. If we consider that the cost of installation is $ 500 pesos per meter, then the total amount spent in replacing and installing new segments of pipelines was 11.2 million of pesos on average.

In order to replace the actual obsolete pipelines plus the pipelines that will become obsolete by 2030, it is necessary to have a replacement rate of 340 kilometres per year; at a cost of $ 500 pesos per meter, the total amount of money needed would be 170 million pesos. If we subtract the cost of the average amount spent from 2005 to 2010 from the 170 million, then SIAPA needs to plan an increase of 158.8 million of pesos per year in investments. The problem in the future, for SIAPA, lies in the amount net earnings obtained; from 2002 to 2009 the average earnings were 68.4 million pesos, with 2007 having a positive result of 174,4 million pesos and 2005 with a loss of 165.5 million pesos. Looking at this numbers, SIAPA will require a subsidy of 90 million pesos per year on average, only considering pipeline replacement; obviously this quantity will increase if more projects are planned (new water sources, new wastewater treatment plants, etc.).

4.4.6 Waste water treatment

From 2000 to 2009, an average of 7.7 m^3 of wastewater was produced in the city of Guadalajara; in other words, 59.86 m^3 per capita per year. Taking this average production as a basis and considering the expected population growth for the next 20 years calculated by CONAPO, a forecast for wastewater production in cubic meters per second can be formulated (Figure 4.47).

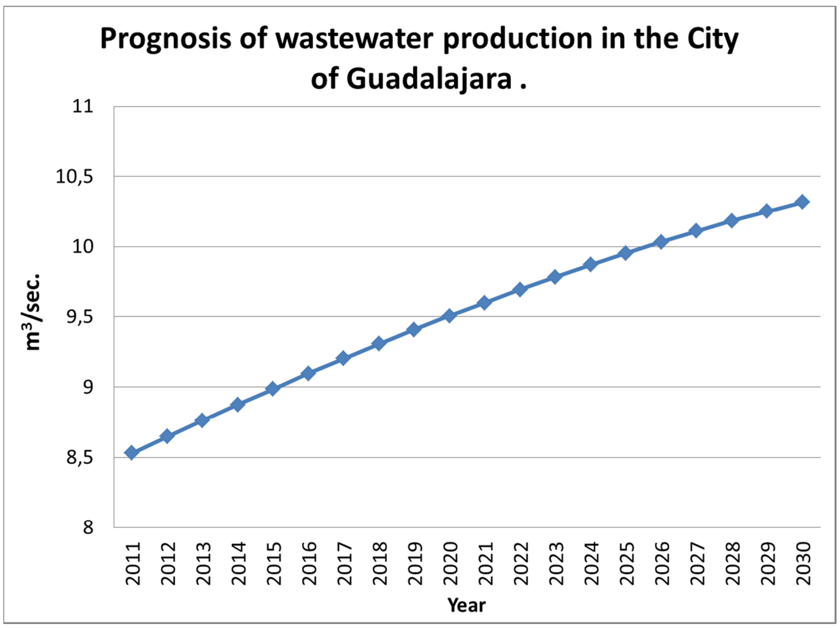

Figure 4.47: Wastewater production prognosis for the city of Guadalajara for the period from year 2011 to year 2030

By the year 2030, 10.3 m^3/sec of wastewater are expected to be produced by the city of Guadalajara, therefore it is necessary to have the infrastructure capable of treating that amount of wastewater produced. In Guadalajara, a big wastewater treatment project represented by the expansion of the treatment capacity of the wastewater treatment plant in Agua Prieta, and the building of the wastewater treatment plant El Ahogado is ongoing. Together, they are expected to treat 10.7 m^3/sec when working at full capacity. This represents the ability to treat all the wastewater produced by the city.

Even though in the voice of the authorities, this project will solve the lack of wastewater treatment in Guadalajara, it has received several criticisms from experts in the field. For example, the points exposed by Gleason during the International Conference on Urban Drainage in Edinburgh, Scotland in 2008 (Gleason et al. 2008), state that the actual impervious surface of the city is between 75-100 % of the total urbanized surface, which means 55 % of the rainfall runoff is collected by the drainage system. As in Guadalajara there are not separate collectors for catching wastewater (grey and wastewater) and rainfall water after run off, both are mixed together in the main collector system causing a deficit in the collection capacity of 50 % during rainy season.

With storm events, several impacts occur in the sewage system as well in the wastewater treatment process. First a flow increase occurs due to the high level of run-off caused by the imperviousness of the surface; this flow may exceed by several times the dry-weather flow capacity of the sewer system, causing overflow, as happens every rainy season in Guadalajara. If the capacity of the collectors are surpassed (as happens when heavy precipitation occurs) part of the mixed rain-wastewater will be discharged into the river Santiago without any previous treatment; therefore it cannot be stated that all wastewater produced by Guadalajara can be treated with both plants if the sewer system does not have two separate collectors, one for rainwater and the other for normal grey/wastewater. In Guadalajara, the average monthly precipitation from 1958 to 2001 in July, the month with most precipitation, was about 147.7 cubic hectometres. Considering the unrealistic situation of non-stopping-equal-intensity rain occurring continuously throughout the month, that would represent 55 m^3/sec; if 55 % of the rainfall is collected by the drainage system, that would mean 19.55 m^3/sec will end in the Santiago River with no treatment received.

Even though rainfalls do not directly affect the wastewater treatment plants, a quick increase of inflow has an impact on the plant in several ways. Due to the garbage on the streets, during storm events the garbage is washed off and captured by the sewage system, which increases the amount of floatable material, which increases the screening caught at the inlet of the treatment plant. Another problem presented when the inflow increases is the primary clarifier efficiency decreases due to the increase in the flow velocity; this situation can be noticeable even after the rainfall event has occurred. Deterioration of aeration tank performance may also occur during a rainfall event, although it is fairly unlikely if the aeration capacity of the plant is sufficient to handle the increased flow and sludge dispense is not disturbed. When the rainwater is combined with the wastewater in the drainage system, the water temperature drops because of the low temperature of rainwater; in low temperature water the bacterial growth processes have lower rates than in dry-season wastewater, which means performance in the activated sludge tank decreases. Also when flow increases occur, that may lead to an increase of solids and organic matter discharge from the second clarifier (in which part of the activated sludge is shifted to from the aeration tank to the second clarifier) directly to effluent, impacting river quality as well decreasing plant efficiency due to the loss of biomass (Schütze et al. 2002).

In conclusion, if the sewer system and wastewater treatment plants are not designed to deal with rainfall events, the overflow caused by rainfalls will be reflected in untreated wastewater being delivered into Santiago River, and the reduction of treatment efficiency. Therefore, it is necessary that construction of a separate collector designed to catch rainwater be contemplated in the infrastructure investment plan.

4.4.7 Expected scenario

If precipitation behaviour remains as it has during the last few decades, and is not drastically affected by climate change, according to the synthetic series performed by IMTA, the volume of Lake Chapala will always be situated over the permissible limit of 2000 hm^3 with an average volume of 4380 hm^3. This volume is necessary to continue supplying water to Guadalajara as it is today. However, it is important to keep in consideration that water coming from Lake Chapala represents only 55 % of the total water supply. Water from subterranean sources is the second main water source; if the extraction/recharge ratio continues as in the last 10 years, the certainty of having no water availability in Atemajac and Toluquilla aquifers is high; meaning that Lake Chapala would remain as the only water source for the city.

Overall, water consumption would remain at 180 L/day per person; even though nowadays the largest population served (SIAPA users) has a domestic water consumption per capita of almost 110 L/day. One reason for this situation is because the neighbourhoods with their own wells have a much higher consumption, and in some cases may reach 400 L/day per person (Usually, wealthy people live in these neighbourhoods and therefore, the houses are considerably big with land extensions of 1000 m^2 or more). No proper control of water extraction is performed by the authorities, and the actual concession system does not support reductions in water consumption.

Not much improvement in water quality is expected; due to the lack of inspectors in PROFEPA, almost no control of wastewater discharges to water bodies by industries exists. Lerma River is one of the most polluted rivers in Mexico, all over its length it receives discharges from different industries without treatment. In the upper part of the river, the discharges come from textile, chemical and metal-mechanic industries, among others; in the middle part, the main pollution sources are petrochemical, tanneries, livestock industries and agriculture; while in the lower part of the river the main contributors are animal farms, particularly pig farms (Lind et al. 2002; Sedeño-Díaz et al. 2007). In fact it is possible to know from which part of the river samples were taken just by determining the pollutants presented in the sample. Because Lerma River is the main water inflow to Lake Chapala, all these pollutants are delivered into the lake after a precipitation event.

Using the information from previous censuses, two curves were built following a logarithmic function. According to the results obtained from these curves, connectivity to the water supply system and drainage system is expected to continue growing in the next 20 years; reaching 97.6 % and 98.3 % of the houses connected to the water supply system and drainage system respectively.

Other aspect that will remain unchanged if SIAPA and the government do not invest in the pipeline renovation is the percentage of water loss in the distribution system. We saw already, that with the actual replacement rate, by 2030 the amount of pipelines exceeding their working life will be over 6000 kilometres. Under these conditions, making a linear relationship between the amount of pipelines expected to be obsolete by 2030 and the percentage of water loss, we can expect that by 2030 between 55 and 65 % of water injected to the supply system would be lost due to the bad condition of the pipelines. Moreover, due to the necessary investments for replacing the pipelines and looking at other water source alternatives, if these investments are made then, financially, SIAPA will be unsustainable. As was presented before in figure 4.46, the investments of SIAPA after year 2003 were on average around 116 million pesos; the amount of money needed to replace the obsolete pipelines is 170 million per year; if we add the average earnings on these years, around 50 million, to the 116 million average investment, the 170 million are not reached. Basically, SIAPA does not have the sufficient income, without governmental subsides, to invest in all the projects Guadalajara needs to reach sustainability in water supply.

In the case of wastewater treatment, with the new treatment plant in El Ahogado and the enlargement of the Agua Prieta treatment plant, is expected that 100 % of the waste and grey water produced in the city will be treated before being delivered into the Santiago River. The complications and obstacles the treatment plants will face during flooding events were already exposed; therefore, under rainy conditions wastewater treatment will not be totally performed.

Regarding the socio-economic indicators, as was mentioned before, in developed countries where the GDP per capita is high, the percentage of the population living in poverty and the inequity level are low. Mexico is already a member of the OECD, and is considered together with Brazil, China and India as an emerging economy; however, nowadays, Mexico is facing several issues that are affecting its economic development, such as the drug war started by President Felipe Calderón in 2008 and the world economic crisis (more specifically, the crisis that the EU is facing) are some examples, among others. If the past GDP growth rate in Mexico from 1988 to 2009 is observed, there will be three periods of continued positive growth after a small negative reduction of the GDP; the average growth rate in the three periods was used as the expected growth rate in the next 20 years, supposing the driving forces remain the same. Nevertheless, it has not been determined how the actual socio-political panorama, including the new presidential period ruled by the Revolutionary Institutional Party (PRI) political party will affect the development of GDP, poverty and inequity; it was observed in the data of GDP per capita at prices in 2005USD, in the immediate year after almost each presidential period ruled by PRI exists a drop of GDP per capita.

In the expected scenario, Guadalajara would not reach a sustainable water supply. The overall WSI result is expected to be around 0.53; improving only 0.14 points in 20 years. Even though when Guadalajara drastically improves the treatment of wastewater (from almost nothing to 100 % of wastewater treated), the increase in water loss and the bad state of Atemajac and Toluquilla caused by the overexploitation that makes water availability in Guadalajara still totally unsustainable; the sustainability performance of Guadalajara would be regular. Based on this prognosis, Guadalajara must concentrate its efforts on the restoration of the aquifers, implementing actions focused on their recharge with good quality water. Several options are available in the literature, from infiltration wells, to treated wastewater injection into the subsoil than can be additionally filtered by the soil before reaching the aquifer (like the system implemented in the city of Berlin, Germany). The option of building a dam to satisfy Guadalajara's water necessities cannot be considered sustainable based on the fact that an ecosystem would be affected/destroyed when the dam is constructed. Another front that SIAPA needs to battle is the replacement of the obsolete pipelines; with the actual financial state of SIAPA, they are not going to be able to make the necessary investment to replace the pipelines; therefore the governments of the involved municipalities should plan the resources for the next 20 years in order to renew the water distribution network in Guadalajara.

4.4.8 Best case scenario

In a best case scenario, the storage capacity of Guadalajara will be over 6000 hm^3 by 2030, having a peak of 6900 hm^3 in 2030, and providing sufficient water availability for supplying the city of Guadalajara. Water quality is also expected to improve if the volume of Lake Chapala increases; this situation is explained by the fact that 55 % of water distributed to Guadalajara comes from Lake Chapala; the lake catches a large amount of rain precipitation, so the pollutants get diluted and their concentration per litre diminishes, increasing the water quality level a bit.

Overall water consumption per capita would reach 150 litres per day or less; this means more efficient water use in the commercial and industrial sectors (the domestic sector, if it remains at it is today, has already reached a sustainable water consumption level). Water supply and sewage system connectivity would reach the 99 % or 100 % level in a best case scenario, exceeding the estimates determined by the trend previously presented. Water loss would reduce the minimum level by replacing 340 kilometres of obsolete pipelines per year, reaching around 10 %. Wastewater treatment would be completely treated, where treated wastewater would be reused as much as possible, and two separate collectors for grey-wastewater and rainwater would be built.

Socio-economically, if Mexico keeps a continued economic growth, there would be a point where poverty would remain stable at low levels (as happens in developed countries nowadays) and wealth would be distributed more equitably. Finally, the financial performance of SIAPA would present black numbers, being self-sufficient and not depending on governmental subsides for financing necessary infrastructure projects.

As a personal opinion based on the data and facts presented during this research, Guadalajara will not ever be in the best case scenario. First, climate change is affecting the region, causing an inability to predict with certainty the volume change of the Lake, which is strongly linked with the precipitation behaviour in the region; an example of that is the article published by van Afferden and Hansen in 2004 (van Afferden et al. 2004), in which they developed a model to predict the volume of Lake Chapala, based on data from 1995 to 2000. In their model, they predicted that by 2010 an equilibrium lake volume over 1000 hm^3 would be reached (using data from 1995 as the starting volume), however, the minimum registered in that year was 4816 hm^3 resulting in a difference over 481 % compared with the data predicted by van Afferden and Hansen. The other big water source for Guadalajara is the water extracted from the aquifers under the city; without exact data, the authorities already expressed the aquifers are overexploited, with no plan which includes the implementation of absorbing wells; together with the high level of imperviousness of the city, the chances of recharging the Atemajac and Toluquilla aquifers up to optimal limits are extremely low. If both situations, constant low lake volumes and overexploited aquifers remain, even though having a proper overall water consumption of under 150 litres per person per day; there will not be enough water to supply Guadalajara's water demand in the future.

Guadalajara water distribution system is getting obsolete, causing an actual water loss of over 34 % of total extracted water; therefore a big investment is necessary to replace the obsolete pipelines. As was explained before, in order to renew the water distribution system, an investment of 170 million pesos per year is necessary (in actual prices and without taking inflation in consideration). Considering other projects also necessary for proper water distribution, such as new water sources or renovation of the sewage system (including the construction of separate collectors for grey/wastewater and rain water); is unlikely that SIAPA can finance the necessary investment with the actual income rate of the company, however, increasing water prices is not the solution either. SIAPA is dragging the problems of bad water management from past decades; therefore, local or federal governments will need to subsidize future projects, making SIAPA unable to be financially self-sufficient.

4.4.9 Worst case scenario

In a worst case scenario, Lake Chapala will have average volumes of around 2200 hm^3, reaching some than 2000 hm^3 in a number of years. Toluquilla and Atemajac aquifers would be over exploited until there is no possible recovery. Under these conditions, water supply to Guadalajara will not be guaranteed using the actual water sources, and it would be necessary to import water from other regions, affecting and damaging not only local, but regional ecosystems.

As it was mentioned before, water quality is linked with the volume of water in Lake Chapala, if the volume of the lake increases from the amount of rain precipitation, the pollutants' concentration is reduced, and conversely, in the case that the volume of the lake decreases dramatically, the pollutants' concentration increases causing water quality to diminish. Consequently, in a worst case scenario, where the volume of Lake Chapala drops down to an average of 2000 hm^3, water quality in Guadalajara will decrease also, presenting similar results as in 2001.

Because of the limited water sources in a worst case scenario, the amount of water consumed per person per day it is unlikely to increase; however, with no control from authorities over water extraction from licensed wells granted to rich enclosed neighbourhoods, water supply will not be equally distributed; while the upper classes would receive plenty of water for their needs, the lower classes would suffer from shortages.

If uncontrolled migration of extremely impoverished populations into the city occurs, looking for better economical/job opportunities; then is likely that the illegal settlements in the surrounding areas of the city would increase. These illegal settlements are characterized by lack of basic services such as electricity, water and drainage. Therefore, in a worst case scenario, those settlements would increase, decreasing the percentage of houses connected to the public water supply system and drainage system.

In the case that further economic crises hit the markets, that will be reflected directly in the GDP (as has already happened in 1994 and 2009); based on the strong correlation between GDP and poverty and inequity, a drastic drop of the Mexican GDP may cause an increase in poverty and inequity in Mexico, and therefore, in Guadalajara as well. Also, in the case of an economic crisis, SIAPA would be affected; during the 2009 crisis, and one year after, SIAPA reported losses of 43 and 55 million pesos respectively; therefore, in a worst case scenario where Mexico cannot overcome the next economic crisis, SIAPA is expected to be working with red numbers. With no money to make necessary investments to replace the obsolete pipelines, 65 % or more of the water pumped into the supply system will be lost during distribution, increasing the virtual water demand of the city.

5. Conclusions

The two main objectives of this research have been to develop a trustworthy index for evaluating the sustainability of domestic water distribution systems at a local scale, and to determine if the case under study, the city of Guadalajara, is presently sustainable with regard to the management of its water resources, and in the case that it is not, to determine whether it would reach sustainability within the next 30 years. After finishing the empirical research, both objectives were accomplished; it was possible to determine the current level of sustainability in domestic water distribution for the city of Guadalajara, and to construct three possible scenarios for the next two decades. Moreover, the overall results were compared with data from a reference case, the city of Berlin in Germany, for a period of 8 years.

In implementing the empirical steps, a new methodology for evaluating water quality was used, introducing the utilization of process capability indices for this purpose.

5.1 Water sustainability index for local scale cases

It was possible to build a trustworthy index for evaluating a domestic water supply system at the local scale; making it more sensitive to poor performance and therefore avoiding eclipsing which could lead to an overestimation of the sustainability level revealed by the case study. It has also been demonstrated that the weights play a small role if the indicator values are close to zero, when the geometric mean is used as aggregation method; this situation allows decision makers to focus first on the indicators with extremely low performance, and when these indicators improve, in the indicators with more relevancy. Furthermore, following the rules created by Ebert and Welsch (Ebert et al. 2004), it has been proven that the model is meaningful for determining sustainability, as the same positive and negative changes in the index result were observed when indices were built with raw data and with normalized data.

However, the process of constructing the index was not without problems. One of the biggest obstacles was data availability at the local level. In contrast to the national scale where information for most of the indicators can easily be obtained from different sources like the World Bank, the United Nations or the OECD, at a local scale, information was difficult to obtain, especially on a yearly basis. For example, for such indicators as the connectivity to the water distribution system, connectivity to the drainage system, the Gini index and the percentage of population living below poverty level, yearly data were not available. This specific challenge was addressed by covering the gaps by building trends using historical data from those indicators. Another problem was the difficulty of determining the weights for the indicators. As explained above, the lack of participation of experts in this topic made me find a different solution for determining the weights. Using a scale for grading each indicator according to its direct impact on the environment is a practical solution which allows a proper comparison between several cases under study, because weights are not based on data behaviour which may change from one case study to other, but on a fixed scale equal for all possible cases under study. Nevertheless, after comparing the final results of the weighted and un-weighted indices, it was found that weights do not play a big role in monitoring the level of sustainability in water supply over time; for both cases under study, Guadalajara and Berlin, the same behaviour in the index results was observed between the un-weighted and weighted index.

As a result of this research, it can be concluded that a composite index is indeed a practical tool for monitoring sustainability in domestic water supply systems at a local scale. It is easily possible to identify those indicators which negatively affect the level of sustainability. On this basis, specific strategies can be designed in order to improve the performance of the indicators. For this purpose, it is necessary to carefully collect relevant data on a regular basis (daily, monthly or yearly), depending on the indicator that is used.

This study has also demonstrated that the use of PCIs for evaluating water quality is more accurate than using the distribution mean of the sampled data. This provides decision makers with a more reliable diagnosis of the quality of the distributed water. This will lead to a practice where water quality problems will be recognized that could not be detected before, or where problems will be identified sooner. Water quality indices constructed with PCIs are proven to be more sensitive to changes in water quality than indices constructed with distribution means. Moreover, when quality indices constructed with distribution means showed an apparent improvement in water quality, the use of PCIs revealed that the real performance of water quality worsened, potentially allowing decision makers to set up better action plans.

5.2 Sustainability of domestic water supply in Guadalajara

After analysing the overall result of the water sustainability index together with future scenarios, it is easy to conclude that Guadalajara presently cannot be considered a sustainable city in terms of domestic water distribution, and it is unlikely that it will have a domestic water supply system considered sustainable in the future.

Going in the direction of becoming a megacity, Guadalajara will face several water supply problems, from finding new and sustainable water sources to sanitation problems. Therefore, Guadalajara cannot keep depending on overexploited aquifers and one lagoon, in which its survival depends on good rainy seasons and political water management decisions in the Lerma-Chapala basin (i.a. the redirection of water extraction of Lerma River towards Mexico City). Similarly, it cannot build a sustainable system on the perpetual yet unmet need to have better planning of wastewater handling. It is urgent that Guadalajara make better use of its water resources, and the first step is to improve the distribution system, as was mentioned before. It is not possible that more than 30 % of water supply is lost during distribution, and this situation is expected to worsen if a full replacement of the obsolete pipelines is not implemented. Politicians need to take the risk of disturbing the way of life of the inhabitants for a couple of years in favour of introducing a modernized distribution system, even if a great financial investment is needed, otherwise this problem will worsen with greater consequences. Also, better control of water extraction that has been provided through concessions to private entities (such as gated communities, industrial enterprises, among others) needs to be implemented. Even though these entities have been entitled to install water meters to monitor the consumption, to date no proper control by the authorities is being done, creating semi-legal opportunities for these entities to extract more water than they are allowed to. Moreover, a variety of additional measures are needed in order to come closer to sustainability: more efficient and careful management of the aquifers; installation of infiltration wells that allow for recharging of the aquifers; better control of land use by the authorities. Unregulated land use has turned out to be a severe obstacle during the past years; there are several examples of protected natural areas and natural recharge areas that have been damaged by urbanization and irregular settlement expansion, without any action taken against it by the government. A clear recent example of this development is the construction of the Omnylife stadium as part of the 2011 Pan-American Games facilities, which has been built over a well-known recharge zone for the Atemajac aquifer.

Nevertheless, proper management of water resources is linked to endeavours to find new water sources for Guadalajara. Finding new sources which substitute for Lake Chapala as the main water supplier of the city, and finding water resources in a sustainable way seems to be an almost impossible task. Several projects were suggested in the past, and one of them was almost implemented, but not one of them could be considered a sustainable project. As a clear example of bad strategies followed by the governments of the municipalities of the MZG and state government is the project of the Arcediano Dam. This project promised to be able to obtain drinkable water from the rivers Santiago and Verde, obviously without being able to achieve its ambitious goals. Plans to take water from the Santiago River, which has been considered highly polluted, lacked credibility, and from its very beginning this project was ecologically unviable because the dam would have damaged the local ecosystems of the Huentitan gully.

From my point of view, no sustainable solution exists for the water availability problems of the city; if new dam projects are planned in other rivers, such as in Verde River, up-stream from where the Arcediano project was originally located, or Zurda River, local ecosystems will be affected, conflicting with the principle of sustainable development. Therefore, a cost-benefit analysis must be performed to determine which project will affect the local ecosystems less, while being enough to substitute for Lake Chapala as main water source; all of these should be undertaken only after improving the distribution system, controlling properly water extraction by private entities and re-using all possible treated wastewater.

Water quality is one of the main issues in a sustainable city; the inhabitants of such a city are able to drink water from the tap without any risk of contracting water borne diseases. If Guadalajara wants to achieve this goal, there is no other way than to improve quality levels up to a point where it is possible to supply pipelined drinking water without causing any health risks. It is inconceivable that the majority of the population consume bottled water for drinking and sometimes for cooking purposes: on average, this is 18000 % more expensive than water supplied by SIAPA. In this case, SIAPA must assure that the quality of distributed water is enough for safe drinking. For this reasons, a number of "orchestrated" measures have to be taken: more control over heavy metals in aquifers, prevention of the presence of fecal matters in the distribution system, chlorination and regular cleaning of the pipelines, better chlorination for water coming from wells, etc. However, if SIAPA assures drinkable water quality in the distribution system, it will also be necessary to prevent water from becoming polluted by biological matters inside the houses. In Guadalajara, more than 90 % of the houses have a cistern, a water tank or both; these systems are a perfect reservoir for bacteria, funguses and other pathogens because the water does not constantly circulate. Therefore, cleaning and disinfection of the cisterns and water tanks is suggested. Pipes inside the houses must be checked for the possible presence of lead pipes or lead joints that may cause a chronic intake of lead, and in case of presence, to replace them wherever possible.

On the other side of the water cycle, better management of wastewater is also required. First, a dual wastewater collector system is needed where rain water is collected separately from grey water and wastewater. More wastewater treatment plants are needed; at present, with the El Ahogado treatment plants and the other plants that were in use before, still less than 30 % of the total wastewater produced is being treated. According to the plan of the Agua-Prieta wastewater treatment plant (which is still in construction), 100 % of the actual wastewater produced will be treated, however, both plants have a useful life of 30 years, according to CEA; that means new water treatment plants must be constructed in the meantime or rehabilitation of both treatment plants need to be performed prior to when the 30 years are over.

Even though this research has been only focused on domestic characteristics of the water cycle, I have the urge to mention the lack of control in industrial wastewater treatment; several industrial facilities causing water pollution are located in the city of Guadalajara; the most important industrial settlement being the industrial park of El Salto It is well known that several national and international companies which have their factories on this industrial site are great contributors to the low water quality of the Santiago River; therefore, even with Agua Prieta and El Ahogado wastewater treatment plants established, no full solution of wastewater problems in Guadalajara will happen if these companies will be allowed to continue to treat their wastewater on their own. In the case that this practice is continued, better control by the authorities (in this case CEA and CONAGUA) must take in place, and the strongest standards for wastewater treatment need to be defined. However, after having witnessed several actions taken against the environment in Mexico just for reasons of protecting economic or political interests, I doubt that any action from the Mexican government to punish the polluting companies, to make them treat their wastewater properly, or to implement better controls to assure all required standards will really take place. Any change on this matter, if it ever occurs, will come from the citizens. Pressure generated by public opinion may be the key to obligating all these companies to stop their polluting practices and to start treating their wastewater. It happened before, when the project of Arcediano Dam was stopped and cancelled, and it might occur again.

Guadalajara is currently not sustainable, due to bad water extraction management in the aquifers, the big dependency on the Lake Chapala, the bad condition of the pipelines for water supply and the low level of wastewater treatment. Apparently this situation will not change in the future. In both scenarios, the expected and the best case scenario, full sustainability is not reached. In the expected as well as in the best case scenario, Guadalajara still mostly depends on Lake Chapala for the supply of water, and on the aquifers of Toluquilla and Atemajac which will remain overexploited. Moreover, in the expected scenario, the condition of the pipelines is still a problem that will keep causing water loss during distribution. A tremendous effort will need to be done by the authorities to implement the necessary actions; moreover, public participation in decision making processes must be a key element for better planning strategies, rather than only informing the citizens about top-down planned actions. In this way, citizens will better accept the possible nuisances that these actions might bring about and will know about the benefits to be expected. Apart from that, citizens might contribute to improved water provision by serving as external monitors of the authorities' performance and pricing, or by punishing ruling parties in the next election if the sustainable goals were not reached. Only by means of a holistic improvement in water management, will the city come closer to sustainability and to improving the living standards of its inhabitants.

5.3 Recommendations for further research

One of the main objectives for developing a sustainability index, aside from monitoring of sustainability, is benchmarking across several case studies. The water sustainability index developed during this research can be used to compare the level of sustainability in domestic water supply between different cities and to identify which strategies were implemented for solving the problems presented in each case. In order to make the comparison valid, the cities should have similar characteristics, e.g. with regard to population structure or the type and degree of urbanization.

The next step of this research would be to compare Guadalajara, initially, with three more cities which introduce different contexts of analysis. The four contexts suggested, including Guadalajara's, would be situated in a developing country with water scarcity (Guadalajara), in a developing country with water abundance (Belo Horizonte in Brazil), in a developed country with water scarcity (Barcelona in Spain) and in a developed country with water abundance (Berlin in Germany). Belo Horizonte has similar characteristics as Guadalajara, with a population of around 5.5 million inhabitants; it is a continually growing city which is expected to also become a megacity in the future; however, the big difference from Guadalajara is that Belo Horizonte has abundant water availability. The second city is Barcelona. With an urban zone of more than 5 million inhabitants, Barcelona represents a developed city but with severe problems of water availability. Finally, the third suggested city is Berlin; with population of 3.4 million inhabitants. Berlin, also is considered as a developed city, possesses enough water resources to supply its needs. The expected outcome of this further research will be to identify those aspects that are making the cities sustainable or unsustainable with respect to domestic water consumption; using both the overall index results and single indicators; and to identify the best strategies that have been implemented by the water management entities in each case study.

Moreover it would be interesting to make a comparison between several cities (more than 30, to be statistically significant), by calculating their level of sustainability and comparing each indicator's performance. The main goal of performing this comparison would be to determine if specific indicators' behaviour can explain an increase or decrease in the level of sustainability. For this purpose, I suggest performing a correlation analysis between the indices' results and each indicator's results; maybe with this information it would be possible to determine a function that can explain sustainability changes universally.

In this study, a novel approach to build a water quality index has been explored. As previously mentioned, water quality indicators have been normalized, making use of PCIs for non-normal distributions employing the method created by Chang. Under this method, Cpks are calculated using the distribution mean to divide the non-normal distribution into two half normal distributions with the same mean but different standard deviations. Further research is needed to explore the possibility of using the median or the mode (assuming unimodal distributions) to divide the non-normal distribution; and to compare the results obtained during this research with the ones from future investigations. Also, other methods to calculate the Cpks in non-normal distributions may be analysed to determine if they perform better than the one used here.

Finally, a door has been opened to further research in new methodologies for index development. The use of fuzzy logic or neural networks to build an easy-to-use tool for decision making processes has been recently studied in the literature. If these two approaches can be used to properly measure the level of sustainability in domestic water supply needs to be determined and gives the opportunity to extend sustainability assessment to new frontiers.

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Annexes

A1: Sustainability indicators used in several indices

Table A1 shows the sustainability indicators related to the water supply mentioned by several authors in the literature to build sustainability or water sustainability indices.

Table A1: Sustainability indicators related to water supply mentioned in the literature

	Krajnc et al. 2005	Guimarães et al. 2007	Kang et al. 2002	Esty et al. 2005	De Carvalho et al. 2009	Sullivan et al. 2002	Morin et al. 2006	van den Berhg et al. 2001	Han et al. 2008	Färe et al. 2004	Emerson et al. 2010	Juwana et al. 2012	UN 2007	Ferreira et al. 2005	OECD 2001	Barrera-Roldan et al. 2002	Lee et al. 2007	van Dijk et al. 2005	Chaves et al. 2006	Blanc et al. 2008	**Total**
Environmental indicators																					
Water use	*				*		*	*					*	*	*				*		8
Wastewater treatment	*		*		*		*						*	*	*		*	*	*		10
Water demand		*										*									2
Quality of water		*	*	*	*		*		*		*	*	*		*	*	*	*		*	14
Surface and ground water availability			*	*	*	*	*				*	*	*					*	*	*	11
Vulnerability of resources							*				*										2
Water loss in distribution systems												*		*							2
Social indicators																					
Gini index of income inequality		*																			1
Access to water supply		*				*	*				*	*	*	*		*					8
Access/use of sanitation facilities		*			*	*					*	*	*	*		*	*				9
Health (morbidity and mortality)					*		*														2
Population living below national poverty line													*			*		*			3
Economic indicators																					
GDP										*			*		*	*		*			5

A2: A critique on existing sustainability indices

After the extensive literature review, several sustainability indices to measure sustainability were found; most of them were constructed to measure sustainability in general, and just a few are water related indices.

Among all the indices consulted, the most important ones were reviewed in detail:

- The Environmental Sustainability Index (ESI) and the Environmental Performance Index (EPI), both created by the Yale Centre for Environmental Law and Policy (Yale University) and the Centre for International Earth Science Information Network (Columbia University).
- Water Poverty Index (WPI).
- Human Development Index (HDI).
- Ecological Footprint (EF).
- Environmental Vulnerability Index (EVI).

Environmental Sustainability Index (ESI)

The ESI is composed of five main components which are divided into 21 indicators grouping 76 variables in total. The ESI checks first if there is normality of the data; and for distributions with a skew greater than two, the distribution is transformed by a base 10 logarithm transformation. After the transformation, in case it is needed, the variables are normalized by standardization; to be, afterwards, aggregated by the arithmetic mean (Esty et al. 2005).

Environmental Performance Index (EPI)

The EPI, based on two main objectives: the measurement of environmental stress on human health, and the management of natural resources and the ecosystem health, is composed of 25 indicators describing 10 different policy categories. The EPI normalizes the variables using the max-min method, where the maximum value is the policy target for each specific indicator, and the minimum value is the worst performance value among the countries evaluated. The aggregation method used in this index is the weighted arithmetic mean, where the weights were calculated through PCA or expert opinion (Emerson et al. 2010).

Water Poverty Index (WPI)

The Water Poverty Index (WPI) was created to evaluate the relationship between water availability and poverty (Juwana et al. 2012). The WPI is composed of five components (resources, access, capacity, use and environment). These components are divided into 22 variables; the components are standardized prior to aggregation. The standardized indicators are, afterwards, aggregated by the weighted arithmetic mean (Sullivan et al. 2003). Most of the indicators used in the WPI are RNC, however, a few of them are qualitative indicators.

Human Development Index (HDI)

The HDI was created by UNDP to measure human development based on the average achievements of countries in three specific dimensions: long and healthy life, knowledge, and standard of living (UNDP 2010). The index is composed of three sub-indices (life expectancy index, education index and GDP index); only the education index has more than one indicator, having five indicators in total. All indicators are normalized using the min-max method (only in the case of GDP, the sub-index is transformed with a base logarithm prior normalization). All sub-indices are aggregated using the arithmetic mean.

Ecological Footprint (EF)

The EF measures the intensity of population resources use and waste discharge activities over a specific area in relation to the area´s capacity to supply the resources and to assimilate the waste. For that reason, it is mandatory to be able to track all resources extracted from the area and all waste disposed over it; and the resources and waste can be converted into a biotically productive area which can supply the resources and assimilate the wastes (Wackernagel et al. 1998). The indicators used to calculate the EF are RNC; as we mentioned before, the use of resources and waste assimilation are converted into areas of square kilometres. After the ratios are calculated, the results are aggregated by the arithmetic mean (Böhringer et al. 2007).

Environmental Vulnerability Index (EVI)

The EVI was designed to assess the risk level of current conditions, predicting how the environment will react when future events occur. The EVI is composed of 50 indicators divided into three components (risk of hazards occurring, resistance to damage and damage vulnerability from past events) (Böhringer, et al.2007). The indicators are normalized by scaling each indicator from one to seven, where one is the target value, and seven is the worst value. The aggregation method selected by the creators of the EVI is the arithmetic mean (Böhringer et al. 2007).

As was mentioned in chapter 2, there exist certain rules the researcher must to follow at the moment the index is constructed in order to avoid the problems previously explained in the same chapter. Ebert and Welsch defined certain criteria to select the proper aggregation method depending on what kind of indicators are being used (Ebert et al.2004).

After looking in detail at each of the described indices, three main common points were found. First, no proper rule for selecting the indicators used was mentioned by the authors of these indices; a key step of constructing SD indices is to select proper indicators which describe the holistic characteristic of SD; and some of these indices totally lack a description of sustainability. Second, several normalization methods were mentioned, but the most common one was the min-max linear transformation method; personally, I agree with the use of this method, because it respects the distribution characteristics of the transformed indicators after normalization. On the other hand, the use of standardization as normalization method is inappropriate in the case of SD, because several indicators are far away from being normally-distributed, on this point, the ESI fails, because it assumes all indicators follow a normal distribution. Finally, the indices being discussed in this annex use ratio-scale non-comparable indicators, however, all use the arithmetic, or weighted arithmetic mean as aggregation method. Considering the rules determined by Ebert and Welsch (Ebert et al. 2004), it is inappropriate to aggregate ratio-scale indicators using the arithmetic mean if it is desired that these indices be meaningful. Therefore, the indices previously mentioned cannot be considered meaningful.