Material Flow Analysis of the Urban Water System in Tepic Mexico: Integral Evaluation and Improvement Options

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Gabriela Margarita Espinosa Gutiérrez

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Gutacher:

Prof. Dr.-Ing. Ralf Otterpohl, Technische Universität Hamburg-Harburg

Prof. Dr.-Ing. Kerstin Kuchta, Technische Universität Hamburg-Harburg

Vorsitzender des Prüfungsausschusses:

Prof. Dr.-Ing. Mathias Ernst, Technische Universität Hamburg-Harburg

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GFEU e.V.
c/o Technische Universität Hamburg-Harburg (TUHH)
Institut für Abwasserwirtschaft und Gewässerschutz
Eissendorfer Str. 42
21071 Hamburg
Tel.: +49 – (0)40 – 42878 3207
Fax: +49 – (0)40 – 42878 2684
http://www.gfeu.org

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Abstract

The water management in Mexico currently faces two important challenges: the availability and the quality of the water resources. The average yearly water availability per capita has been decreasing constantly since 1950 and the projections for year 2030 predict a further reduction. Furthermore, a large number of superficial and underground water bodies are polluted. The efforts currently made to counteract these problems in the country include improving the water use efficiency (to ensure future availability) and avoiding further pollution of the water bodies (to protect its quality).

To fulfil these goals in a sustainable manner, an integrated assessment and management of urban Water and Wastewater Management Systems (WWMS) is necessary, as cities are important water consumers and polluters. Conventional approaches for the assessment of WWMS in Mexico, however, are not carried out in an integrative manner and they often exclude the relationships of the systems with the local environment or with natural phenomena. Some drawbacks of the conventional approaches are the usual lack of a complete overview of the water related processes of the city and the exclusion of several flows which are difficult to measure directly, but which are actually taking place in real working conditions and may impact the overall efficiency of the system in a significant manner.

The present research was carried out to evaluate the suitability of Material Flow Analysis (MFA) as a complementary methodology for the integral assessment of WWMS in Mexican small to middle sized cities. The methodology was tested by means of a case study in the city of Tepic, Mexico. For the case study, local partners were engaged and information specific for the city was collected by means of site visits, interviews and documents review. This allowed building a model of the city representing all water related processes, flows and stocks. The model was developed so that it could be further applied to other locations of similar complexity. Besides the water flows, the model considered the nitrogen (N) and phosphorus (P) content of the flows. The MFA in Tepic provided a complete overview of the water related processes of the city and an overall water and nutrient balance (N and P). The sources, paths and destinations of water and nutrients flows were recognized and a first assessment was made for previously ignored and unknown flows.

MFA scenarios for years 2007 and 2011 allowed comparing the city before and after major improvements to the WWMS and made clear that despite the large investments made between those years, two important flows remained unattended which affected the overall efficiency of the system negatively: water infiltration to the sewer and sewer exfiltration to the soil. To better assess the infiltration, N and P measurements were made in sewer samples and a detailed monthly MFA for 2011 was carried out. This allowed for an improved approximation of the infiltration value based on the comparison of the nutrient concentrations in undiluted wastewater with the actual measured nutrient concentrations in the sewer.

The calculated infiltration data was used for projections of the situation in 2030 and this future scenario was used to model three changes of the system that could lead to a more sustainable management: consumption control and reduction, infiltration reduction and management as well as improved rain water management. Additionally, a concept to measure the infiltration and exfiltration in Tepic was developed and the safe reuse of the treated wastewater in the agriculture was discussed.

Thus, it was demonstrated that the use of MFA coupled with a modelling approach is a suitable tool for simulating the impacts of improvement options before decisions are made. With this information, city planners and decision makers are better prepared to implement successful strategies to increase efficiency in water use and to avoid further pollution of the water bodies.

Zusammenfassung

Das Management der Wasserressourcen in Mexico steht vor zwei wichtigen Herausforderungen, nämlich der Verringerung der Verfügbarkeit und der Verschlechterung der Wasserqualität. Die durchschnittliche jährliche Wasserverfügbarkeit pro Kopf sinkt stetig seit 1950. Die Prognosen für 2030 gehen von einer weiteren Reduzierung aus. Darüber hinaus sind zahlreiche Oberflächenwasser- und Grundwasserkörper verunreinigt. Diese Probleme werden mit Anstrengungen bekämpft, eine effiziente Wassernutzung zu fördern und weitere Verschmutzung von Oberflächen- und Grundwasser zu vermeiden.

Um diese Ziele nachhaltig zu erreichen, müssen die städtischen Wasser- und Abwassermanagementsysteme (SWAS) einheitlich evaluiert werden, da Städte wichtige Wasserverbraucher sind und auch eine erhebliche Verschmutzungsquelle darstellen. Die konventionellen Ansätze, um SWAS in Mexiko zu evaluieren, sind nicht integrativ und berücksichtigen oft nicht die Wechselwirkungen zwischen den SWAS und der lokalen Umwelt oder Naturereignissen. Ein Nachteil der konventionellen Ansätze ist, dass sie üblicherweise keine komplette Übersicht über die mit Wasser in Beziehung stehenden Prozesse der Stadt geben. Ein weiterer Nachteil ist, dass sie mehrere Ströme ignorieren, die schwierig direkt zu messen sind, aber einen erheblichen Einfluss auf die Gesamteffizienz des Systems haben können.

In der vorliegenden Forschungsarbeit wurde die Praxistauglichkeit der Stoffstromanalyse (auf Englisch Material Flow Analysis, kurz MFA) als komplementäre Methodik für die ganzheitliche Evaluierung der SWAS in kleinen und mittelgroßen Städten Mexikos anhand des Beispiels der Stadt Tepic getestet. In der Fallstudie wurden lokale Projektpartner mit einbezogen, und es wurden spezifische Informationen über die SWAS in der Stadt durch Standortbesuche, Expertenbefragung und Dokumenteneinsicht gesammelt. Mit den gesammelten Informationen wurde ein Model der SWAS der Stadt aufgebaut, das alle wasserrelevanten Prozesse, Stoffströme und Stofflager abbildete. Das Model wurde so konzipiert, dass es leicht an andere Orte mit ähnlicher Komplexität angepasst werden könnte. Außer den in der Stadt auftretenden Wasserströmen berücksichtigt das Modell auch deren Stickstoff (N)- und Phosphor (P)-Gehalte.

Die MFA der SWAS in Tepic lieferte ein vollständiges Bild der wasserrelevanten Prozesse in der Stadt und eine Gesamtbilanz für Wasser und Nährstoffe (N und P). Quellen, Pfade und Verbleib der Wasser- und Nährstoffströme wurden erkannt, und eine erste Bewertung für bisher nicht evaluierte Stoffströme in der SWAS in Tepic wurde durchgeführt. MFA-Szenarien für die Jahre 2007 und 2011 ermöglichten es, die SWAS der Stadt vor und nach größeren Verbesserungen zu vergleichen. Die Ergebnisse zeigten, dass trotz der großen Investitionen in das System, die zwischen diesen beiden Jahren getätigt wurden, zwei wichtige Stoffströme unbehandelt blieben und immer noch die Gesamteffizienz des Systems negativ beeinflussten: Infiltration von Fremdwasser in die Kanalisation und Exfiltration aus der Kanalisation. Um den Fremdwassereintrag besser abschätzen zu können, wurden N- und P-Messungen in Abwasserproben entlang der Kanalisation durchgeführt. Mit diesen Informationen wurde eine detaillierte monatliche MFA für das Jahr 2011 durchgeführt. Dies ermöglichte eine verbesserte Abschätzung des Fremdwassereintrags basierend auf dem Vergleich der Nährstoffkonzentrationen in unverdünntem Abwasser mit den tatsächlichen in der Kanalisation gemessenen Nährstoffkonzentrationen.

Die berechneten Infiltrationsdaten aus dem detaillierten Szenario für 2011 wurden für Projektionen der Situation im Jahr 2030 verwendet. Mit diesem detaillierten Zukunftsszenario wurden drei Veränderungen des Systems getestet, die zu einem nachhaltigeren Management führen könnten:. Kontrolle und Reduzierung des Wasserverbrauchs, Reduktion der Infiltration von Fremdwasser in die Kanalisation und verbessertes Management des Regenwassers. Darüber hinaus wurde ein Konzept erarbeitet, um die Infiltration von Fremdwasser und die Exfiltration aus der Kanalisation in Tepic zu messen. Schließlich wurden Möglichkeiten für die sichere Wiederverwendung des behandelten Abwassers in der Landwirtschaft diskutiert.

Es konnte gezeigt werden, dass die Benutzung von MFA in Kombination mit einem Modellierungsansatz geeignet ist für die prädiktive Simulierung der Effekte von Verbesserungsvorschlägen, um so wertvollen Informationen für den Entscheidungsprozess zu generieren. Mit diesen Informationen sind Entscheidungsträger besser vorbereitet, um erfolgreiche, nachhaltige Strategien umzusetzen, die die Effizienz der Wassernutzung verbessern und die weitere Verschmutzung von Oberflächen- und Grundwasser vermeiden.

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Abbreviations and symbols

Abbreviation or symbol	Definition
a	Annum (year)
ADF	Average daily flows
AI	Additions by infiltration
AOP	Advanced Oxidation Processes
AWI	Additional water import
BMBF	Bundesministerium für Bildung und Forschung (German Federal Ministry of Education and Research)
BOD	Biological oxygen demand
COD	Chemical oxygen demand
CONAGUA	Comisión Nacional del Agua (Mexican Water Commission)
CONAGUA Nayarit	Comisión Nacional del Agua en Nayarit (Water commission for the state of Nayarit)
CSO	Combined sewer overflow
DOC	Dissolved Organic Carbon
DWA	Deutsche Gesellschaft für Abwasserwirtschaft, Abwasser und Abfall (German Association for Water, Wastewater and Waste)
€	Euro (exchange rate 20 March 2015: 1 € = 16.319 MXN$ in OANDA)
EUWFD	European Water Framework Directive
FAO	Food and Agriculture Organization of the United Nations
g	gram
GDP	Gross Domestic Product
GWh	Gigawatt hour
ha	Hectare

HAR	Hydrological-Administrative Region
HOGV	Health-oriented guidance value
I/I	Infiltration and inflow
INEGI	Instituto Nacional de Estadística, Geografía e Informática
IPSWaT	International Postgraduate Studies in Water Technologies
inh	Inhabitant
IS	Infiltration share
kg	Kilogram
kms	Kilometre
L	Litre
LCA	Life cycle assessment
LUBW	Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (Baden-Württemberg State Institute for the Environment, Measurements and Nature Conservation)
m	Meter
μg	Microgram
MAPAS	Manual de Agua Potable Alcantarillado y Saneamiento (guidelines for drinking water and sewer services)
MDF	Minimum daily flows
MFA	Material flow analysis
mg	Milligram
Mio	Million
mm	Millimetre
MWA 2030	Mexican Water Agenda 2030 (Agenda del agua 2030)
MXN$	Mexican peso
NGO	Non-governmental organizations
NI/ND	Non-Industrial/Non-Domestic
Ntot	Total nitrogen
PJ	Peta Joules
Ptot	Total phosphorus
REPDA	Registro Público de Derechos del Agua (Public registry of water use rights)
s	second

SC-Method	Simplified chemical method
SEMARNAT	Secretaría de Medio Ambiente y Recursos Naturales
SIAPA Tepic	Sistema de Agua Potable y Alcantarillado de la ciudad de Tepic (Public company for water supply and sewer works company in Tepic)
STAN	STOffstromANalyse (software for Material Flow Analysis)
t	Tonne
TC	Transfer coefficient
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TPS	Terra Preta Sanitation
TRWR	Total Renewable Water Resources
TSS	Total Suspended Solids
UAN-ACBI	Universidad Autónoma de Nayarit, Unidad Académica de Ciencias Básicas e Ingenierías (University of Nayarit, academic unit for basic science and engineering)
UAN-CUCSH	Centro Universitario de Ciencias Sociales y Humanidades de la Universidad Autónoma de Nayarit (Department of social sciences and humanities of the university of Nayarit)
USA	United States of America
USEPA	Environmental Protection Agency of the USA
WHO	World Health Organisation
WW Sewer	Wastewater sewer
WWMS	Water and wastewater management system
WWP-Method	Wastewater production method
WWTP	Wastewater Treatment Plant

Chapter 1

Introduction

1.1 Status of water resources in Mexico

Natural conditions

The location and altitude of Mexico causes a wide variety of climates. Whereas there are arid and semi-arid conditions in the north with precipitation values below 500 mm a^{-1}, there is a humid climate in the south where the precipitation may reach values above 2,000 mm a^{-1} (Comisión Nacional del Agua [CONAGUA] 2011). As a national average, the precipitation is 758 mm a^{-1} (Food and Agriculture Organization of the United Nations [FAO] 2015). The Total Renewable Water Resources (TRWR), also known as natural available water or renewable freshwater resources, indicates how much water is available in a country for its activities after consideration of the natural water inputs and outputs in the territory. In Mexico, the TRWR amounts to 471.5 km^3 a^{-1} (CONAGUA 2013).

The TRWR tends to stay constant. However, the TRWR per capita is subject to changes according to the number of inhabitants. The TRWR per capita in Mexico has decreased largely in the past 60 years. The population in Mexico quadrupled between 1950 and 2010 and currently the population number of Mexico is 112 Mio. inhabitants (Instituto Nacional de Estadística, Geografía e Informática [INEGI] 2012). Due to this impressive growth, the average TRWR per capita has decreased from 17,825 m^3 a^{-1} inh^{-1} in 1950 to 4,097 m^3 a^{-1} inh^{-1} by 2010. The projections for 2030 predict with a further reduction of the availability to 3,800 m^3 a^{-1} inh^{-1} (CONAGUA 2011). This national average is not considered as water scarcity. The FAO considers that water stress is characterized by a per capita TRWR of 1,700 m^3 a^{-1} inh^{-1} or below (FAO 2015). Yet, a reduction of 75% of the water availability in only 60 years is alarming.

Table 1.1 presents a list of selected countries showing different aspects of their water resources. The selection of countries was done to include locations with extreme poor and extreme rich conditions of their water resources. It is observed that Mexico, in average, is not in an extreme situation for any of the shown parameters. However, the water availability per capita differs largely amongst the regions and some of them live under extreme favourable conditions whereas other live under continuous water stress and water scarcity. For example, at the southern frontier of Mexico, there is a water availability of 22,185 $m^3\ a^{-1}\ inh^{-1}$. In the region known as *Valle de México* where Mexico city is located, the availability is only 164 $m^3\ a^{-1}\ inh^{-1}$. This last figure is considered by the FAO as absolute water scarcity (CONAGUA 2013). Additionally, the seasonal character of the precipitation in Mexico also has a serious negative impact on the water availability during the dry season since 68% of the yearly precipitation takes place from June to September (CONAGUA 2011).

On the other hand, recent statistics about the contribution of the Mexican Hydrological-Administrative Regions (HAR)[1] to the national Gross Domestic Product (GDP) found that by the end of 2013, 53% of the population lived in regions where 64% of the GDP is produced but only 17% of the available water is located (CONAGUA 2014). That means that the most productive areas of the country, such as Mexico city and its surroundings, are located in areas of water stress.

Uses and sources of the water

The Mexican Public Registry of Water Use Rights (*Registro Público de Derechos del Agua*, REPDA) manages all the information regarding the permits for water use, including the abstraction of groundwater or superficial water and the discharge of wastewater to water bodies. According to the REPDA, the agricultural sector is responsible for 77% of the water consumed in the country. The public supply of water accounts for 14% of the water consumed, the industrial applications for 4%. The generation of electricity in facilities other than hydropower plants, i.e. geothermal plants, carbon combustion, etc., account for 5% of the national consumption [2]. From the totality of water used for productive purposes, 62% is obtained from superficial water bodies such as rivers and lakes. The remaining 38% is obtained from groundwater sources. The agricultural sector relies more on superficial water sources (65% of total abstraction) whereas the public sector and the industry rely more on groundwater sources (60% and 57% of total abstraction, respectively). The trend observed in the last years indicates a general increasing dependency on groundwater sources (CONAGUA 2013).

With a total TRWR of 471.5 $km^3\ a^{-1}$ and 82.7 $km^3\ a^{-1}$ of abstracted water (official figure for the granted concessions of water abstraction from all sources,

[1] The water basins in Mexico are organized into 37 hydrological regions. To facilitate the integration of these regions with socio-economical information, they are organized into 13 Hydrological-Administrative Regions.

[2] These statistics refer to the consumptive uses of the water (CONAGUA 2011). The use of water for electricity generation at hydro power plants is considered separately.

Table 1.1: Fresh water resources in the world according to the FAO.

Country	Precipitation (mm a^{-1})	TRWR (km^3 a^{-1})	TRWR cap (m^3 a^{-1} inh^{-1})	Water stress (%)
United Arab Emirates	78	0.15	16	1,867.00%
Qatar	74	0.06	27	374.10%
Egypt	51	58.30	710	97.82%
Ethiopia	848	122.00	1,296	4.56%
India	1,083	1,911.00	1,526	33.88%
Germany	700	154.00	1,862	20.95%
China	645	2,840.00	2,005	19.51%
Spain	636	111.50	2,376	28.57%
Iraq	216	89.86	2,661	73.44%
Mexico	***758***	***461.90***	***3,776***	***17.21%***
United States of America	715	3,069.00	9,589	15.49%
Malaysia	2,875	580.00	19,517	1.93%
Panama	2,928	139.30	36,051	0.74%
Brazil	1,761	8,647.00	43,157	0.86%
Colombia	3,240	2,360.00	48,840	0.50%
Canada	537	2,902.00	82,485	1.45%
Iceland	1,940	170.00	515,152	0.10%

Source: data obtained from the Aquastat data base of the FAO (FAO 2015). The reference periods might differ for each country.
Explanation of column headers:
Precipitation: Long-term average precipitation in units of depth.
TRWR: Total renewable water resources (actual).
TRWR cap: Total renewable water resources per capita (actual).
Water stress: Freshwater withdrawal as % of total actual renewable water resources.

as found in CONAGUA 2013), the degree of stress over the water resources in Mexico is 17%, expressed as percentage of renewable freshwater resources withdrawn for consumptive uses. This is not considered as water stress by the FAO (FAO 2015), however this is a national average and as mentioned before, the water and the productive activities as well as the population are not distributed homogeneously along the country. As a consequence, there were 100 aquifers in Mexico in conditions of overexploitation by the end of 2009 (CONAGUA 2011). By the end of 2012 the number had increased to 106 (CONAGUA 2013). Furthermore, the central, north and north-east regions of the country live under conditions of water stress since the 40% threshold value set by the FAO is exceeded at these locations (Arreguín Cortés and Mejía Maravilla 2011).

Urban water use

Urban water supply has been identified as one of the most critical factors in determining the future growth of Mexican cities (Martinez et al. 2010). Many global environmental and resource issues can be directly attributed to consumption and waste generation within urban environments (Sheehan and Starke 2007). Overall, human excreta are the principal vehicle for the transmission and spread of communicable diseases (Feachem et al. 1983). For these reasons, the topic of interest for the present research is the urban use of water.

Urban environments are not always the largest sources of pollution. Especially in developed countries, agricultural activities may represent a larger pollution source in terms of nutrients. Nevertheless, the urban environments can be a powerful and responsive "control handle" for pollution prevention and for integrated river basin management (Benedetti et al. 2006).

In matters of urban water use, the three most relevant indicators are: the coverage of drinking water services and of sanitation services as well as the degree of wastewater treatment. The Mexican Water Commission (*Comisión Nacional del Agua*, CONAGUA) considers a citizen has access to drinking water, when the person has access to piped water from the public water system in his/her own home or his/her own premises or if the access is guaranteed by a public tap or by a neighbour. The quality of the water does not necessarily has to be of a quality for human consumption. With respect to access to public sanitation, the CONAGUA considers coverage when a home is connected to the public sewer system and also when it is supplied with a septic tank or when it simply is provided with a drainage not necessarily discharging to the public sewer system but to a river, a creek, etc. (CONAGUA 2011).

According to the definitions above, the coverage of the drinking water services by the end of 2011 was 91.6% of the total population. The coverage of the public sanitation services was 90.2%. These percentages are higher in urban areas, with an average of 95% of access to drinking water and 96% coverage of sanitation services.

In the topic of wastewater treatment, Mexico has made important improvements in the last years by doubling the treatment capacity between 2000 and 2011. In 2000, 45.9 m^3 s^{-1} of wastewater were subjected to treatment. By the end of 2011, the municipal treatment facilities were treating 97.6 m^3 s^{-1} of wastewater, equivalent to 46.5% of the (theoretical) volume of collected wastewater (CONAGUA 2012).

Figure 1.1 shows a summary of the official figures for municipal wastewater generation, collection and treatment in 2009, 2011 and 2013. It is undeniable that improvements have been achieved. The ratio of uncollected wastewater has been reduced and the ratio of wastewater undergoing any kind of treatment has been increased. Nevertheless, these official figures are calculated based on the population number and the theoretical wastewater production derived from this data. The actual wastewater production is not measured and the actual water consumption of the population is not measured everywhere. For example, in cities with more than 50,000 inhabitants, the consumption is measured only at 51% of the homes on average. In some cities the measurement may cover up to 97% of homes but in other cities no measurement devices are installed at all (CONAGUA 2012). Therefore, the actual generation of municipal wastewater may be larger.

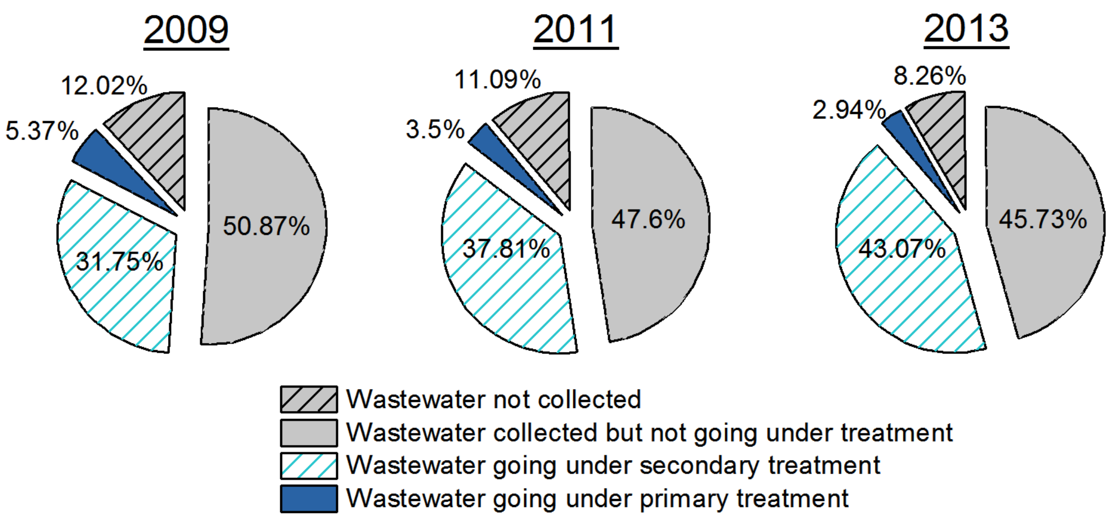

Figure 1.1: Evolution of wastewater treatment in Mexico in recent years.
Source: based on CONAGUA 2010, 2011, 2012, 2013 and 2014.

The treatment coverage of non-municipal wastewater is not as good as the coverage for municipal wastewater shown in Fig. 1.1. The official sources report 210.26 $m^3\ s^{-1}$ of wastewater generated by non-municipal sources including the industry (CONAGUA 2014). Numerous private facilities treat 60.75 $m^3\ s^{-1}$ of industrial wastewater and it represents 81% of the installed treatment capacity of these private facilities. The treatment coverage for non-municipal wastewater is therefore 29%. This 29% is composed of 10% primary treatment, 15% secondary treatment and 1% tertiary treatment. The remaining 3% is unspecified in its treatment type. In theory, the untreated wastewater is directly discharged water bodies (CONAGUA 2014). In practice, however, it can also be discharged to the public sewer system where it is mixed with municipal wastewater (Cardoso Vigueros et al. 2000).

In urban areas, there are other problems besides the deficit in treatment capacity for wastewater. The ineffective operation of the water systems is one of them. The low level of maintenance in some locations leads to large physical losses (Hazin 1997) and overflow and leakages of sewer systems represent an important pollution source for urban aquifers (Martinez et al. 2010). Additionally, there has been historically a heavy financial subsidy in the water sector. Together with the general belief that water should be supplied at very low cost or no cost at all and with the fact that the water services are perceived as of low quality, there is a general resistance of the population to price increases in the water services and in some sectors there is a reluctance to payment at all. The production costs of drinking water and treatment costs of the wastewater often have to be subsidized by the federal government and some municipalities work under conditions of continuous bankruptcy (Hazin 1997, Rodriguez Briceño 2008, Montero Galindo 2010). The existence of illegal users and the lack of measurement devices also contribute to the problem (Martinez et al. 2010). On a national level, the revenues of the CONAGUA represent only 33% of the spent budget (CONAGUA 2013). The remaining 67% of the expenses has to covered by subsidies.

According to Hazin (1997) and Rodriguez (2008) the lack of continuity in policies and programs and the lack of accountability together provide no incentives for the municipalities to establish long-term water planning. Furthermore, there is a lack of technical capacity and human resources at some locations, which limits the proper administration of the water resources in the cities.

Quality of the water resources

Given the low degree of wastewater treatment in the country in the past and presently, the water quality in Mexico is of concern. Until 2003 Mexico was using an integrated index of water quality (*Indice de calidad del agua*, ICA) which grouped 18 different physical and chemical parameters in a weighted manner. According to this index, 53% of all monitored superficial water bodies presented some degree of pollution in 2003. Amongst them, 23% presented a moderate degree of pollution and 11% were highly polluted (Secretaría de Medio Ambiente y Recursos Naturales [SEMARNAT] 2005).

Currently three parameters are officially used to monitor the water quality: Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and Total Suspended Solids (TSS). A COD concentration above 40 mg L^{-1} is considered as pollution. Below this value, the water quality is considered as acceptable. For BOD the threshold value is 30 mg L^{-1} and for TSS it is 150 mg L^{-1} (CONAGUA 2014).

In 2009, there were 1,510 monitoring sites all over the country. It was determined that 21 water basins in the country were highly polluted regarding one or several water quality indicators. According to the mentioned threshold values, 31% of the monitored superficial water bodies showed some level of pollution in terms of COD, 15% presented some level of pollution in terms of BOD and 7.5% presented pollution due to TSS (CONAGUA 2011).

By the end of 2013, the monitoring network has grown to over 5,000 sites. However, the situation has not improved: 44% of the monitored places showed some level of pollution in terms of COD, 9% presented some level of pollution in terms of BOD and 14% presented pollution due to TSS. It was also determined that a total of 260 monitoring sites in the country were highly polluted regarding one or several of the mentioned water quality indicators (CONAGUA 2014).

In the European Union the standard quality indicators for assessing the status or water bodies do not include COD, BOD or TSS. According to the European Water Framework Directive (EUWFD) to evaluate the status of a water body, it is necessary to evaluate its ecological, and chemical status as well as its ecological potential[3]. Among the chemical and physico-chemical elements supporting the biological elements[4] the following can be found: thermal conditions, oxygenation conditions, salinity, acidification status and nutrient conditions (in the case of lakes and coastal waters, transparency is also a criterion). According to the EUWFD, water bodies are classified in one of five categories of ecological status: high, good, moderate, poor and bad (EU 2000).

Due to differences between Mexican and European quality standards, a direct comparison is not possible or meaningful. However, some authors relate the BOD with the ecological status classification. According to Wagner (2006) a water body with high ecological status has a BOD of around 1 mg L^{-1}, one with good status has a BOD normally of 2-6 mg L^{-1}, with moderate status the BOD lies often between 7-13 mg L^{-1}, and with poor status the BOD is already >15 mg L^{-1}. Förstner (1998) considers that when BOD is above 5 mg L^{-1} it can be classified as critically polluted. Compared to these criteria, the number of polluted water bodies in Mexico could be larger than currently considered by the official classifications. Nowadays in Mexico, water bodies with a BOD load of 6-30 mg L^{-1} are still classified as acceptable (non-polluted).

The information about water-related diseases can also be used as an indirect indicator for water resources quality and management in a country. In 1992, the health costs of water pollution in Mexico were estimated to amount to US$3,600 million. This estimate includes the cost of diarrhoeal diseases caused by water and soil pollution, as well as by the lack of sanitation and by food poisoning (Margulis 1992). In 2007, 5.5 million people in Mexico were affected by intestinal infections. The infection rate has been increasing over the years and this fact highlights the need of paying attention to hygiene and wastewater management practices in order to avoid water-related diseases (CONAGUA 2008).

1.2 Improvement efforts in Mexico

The CONAGUA has recognized that prevention and control of pollution represents an important challenge in water management (Arreguín Cortés and Mejía

[3] For groundwater only chemical status.

[4] As biological elements following are understood: phytoplankton, aquatic flora, invertebrate fauna and fish.

Maravilla 2011). It is also known that the root cause for water pollution problems is the lack of control on pollution sources (Jiménez 2008).

The reaction of the government and regulatory bodies to water problems started already in the decade of the 90's when important investments in the water sector were made. Nevertheless, priorities back then were different. For example, in 1995 the largest investments were made in the agricultural sector (64% of investments) and in the increment of drinking water coverage (26% of investments). The investments in wastewater treatment amounted only to 1% (Hazin 1997). The structure of the expenditures of the CONAGUA has evolved over the years and currently almost 70% of the total expenditure is applied to the sectors of drinking water supply, sewerage and sanitation together. The expenditures in wastewater treatment alone accounted for 35% and 18% of total expenditure in years 2012 and 2013, respectively. Figure 1.2 shows the evolution of the expenditures of the CONAGUA in the past years.

The Mexican authorities recognized that the population increase will generate an enormous challenge for the country. Some of the HAR where the largest growth is expected, are already under water stress. The CONAGUA considers that it will be necessary to reduce water demand per capita through an increase in the efficiency of agricultural use and an increase of the efficiency of the distribution networks of cities (CONAGUA 2013).

With respect to availability and quality of water resources, the country is currently banking on measures directed towards the improvement of the water use efficiency and towards avoiding further pollution of water bodies by increasing the wastewater treatment coverage. The Mexican Water Agenda 2030 (MWA 2030, *Agenda del Agua 2030*) released in 2011 by the CONAGUA proposes long term strategies to achieve a sustainable management of the water resource based on assessments carried out at a national level. Among the strategies proposed by the MWA 2030 it is included to connect the suburban city areas to the drinking water and sewerage networks, to operate these networks efficiently, to treat all municipal wastewater and to reuse all treated wastewater (this last objective to be achieved after year 2030) (CONAGUA 2011).

In the framework of this thesis, a separate study was carried out by Rámirez Meneses (2013) clarifying further details about the actual conditions of freshwater resources and the handling of wastewater in Mexico. The study also examined the water management tools available within the Mexican legal and institutional frames.

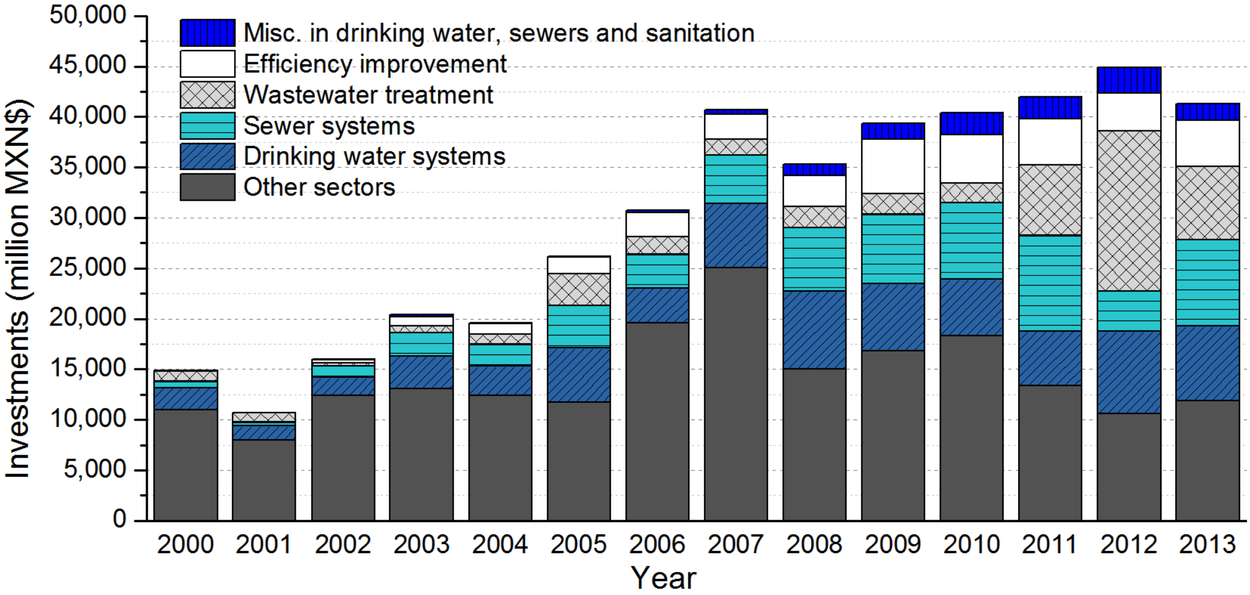

Figure 1.2: Evolution of expenditures in the water sector.
Includes only the expenditures by CONAGUA.
Source: based on CONAGUA 2014 and CONAGUA 2015

Need for integrated assessment of urban water management

The progress achieved in all objectives of the MWA 2030 is to be reviewed yearly and the impacts and results obtained shall be evaluated every six years. The Water and Wastewater Management Systems (WWMS) need to be evaluated on a regular basis. However, it is not an easy task to evaluate WWMS. To assess the efficiency of the systems and to evaluate its potential impacts on the environment, several questions need to be answered with real data and not only on the basis of theoretical calculations. The questions are:

- How much water is actually consumed by which users?
- How much wastewater is generated?
- How much wastewater reaches a treatment facility and where does the remainder go?
- How large is the pollutant load in the wastewater streams and which are the disposal routes?
- Is the quality of the wastewater (treated or not treated) appropriate for its discharge to water bodies or for its reuse?

It is necessary to compile more information about the sources, volumes, pollutant loads and destinations of water and wastewater in the cities. For the design and construction of drinking water and sewer systems as well as for treatment facilities, there is an extensive collection of separate guidelines, norms and technical recommendations in Mexico (for a summary consult CONAGUA 2010), which are based on the best available technology and expertise. These guidelines usually serve as a comparison basis for the separate evaluation of each of the elements of WWMS. The integral evaluation of all the components of the WWMS together is not the rule in conventional approaches.

The assessment of separate elements of the WWMS, however, is inappropriate because they represent interdependent service functions (Heaney et al. 2000). Water supply and sanitation are interlinked processes of the urban water cycle and the planning of WWMS should be holistic and realistic (PADCO 2001). Urban water and wastewater must be analysed in terms of the urban water balance (Eiswirth 2002). In conventional approaches, some factors which are difficult to be directly assessed may not be included. These factors include interactions of the WWMS with the local environment and with natural phenomena, as well as the interactions between old and the new infrastructures. Factors like these often are only partially integrated in conventional evaluations due to the difficulty of their assessment . As a consequence, some flows, such as water infiltration and sewer exports, may be excluded or denied. These flows are actually taking place under real conditions and may have an important influence on the overall efficiency of the system. It is relevant for the development of sustainable strategies, to plan the actions in close relationship with real conditions and consider the WWMS as a whole. A merely partial assessment could lead to the implementation of measures which do not provide a sustainable solution for the future and generate only a short term improvement.

1.3 Integral evaluation of urban water systems

"Quantifying the urban water and contaminant balance, and detailing the flow paths and contaminant concentrations within the urban water system, is a way of moving towards the goal of more sustainable systems" (Mitchell and Diaper 2005, p. 91).

The evaluation of a system should not be confused with a decision making process. The evaluation of a system or of system alternatives, is the first necessary step of any decision process. For example, Malisie (2008) applied the methodology of sustainability assessment to three different sanitation options in the sub-urban areas of Surabaya in Indonesia. With this methodology, the sanitation options were evaluated in terms of economic, environmental and social aspects. To choose the most feasible and sustainable sanitation system amongst the three options, the information obtained from the sustainability assessment was used in a multi-criteria decision making approach, namely in the Analytic Hierarchy Process.

An evaluation can also take place independently of a decision process in order to investigate and determine the current status of the system, to compare before-after conditions, to assess if there is need of action or to assess the progress towards a specific objective.

In urban environments, the evaluation of the water discharges and the evaluation of the discharged contaminant loads is a useful first step in assessing the impact of such systems on the environment. To make a decision, the information obtained needs to be interpreted in the context of the specific location (Eiswirth 2002). The present research focuses exclusively on the integral evaluation of the WWMS of a Mexican city under different scenarios and on the use of the obtained information for decision making.

Several different approaches have been used for the integral evaluation of urban WWMS. With respect to integral evaluation of WWMS, the following terms are frequently used in literature: urban water balance, urban water cycle, urban water metabolism and water budget. It is the same concept that lies behind all those terms: mass balancing. A mass balance quantifies the imports and exports of materials and substances to and from a process as well as the depletion of internal resources or their accumulation inside the process boundaries. The term "water balance" is used to account for the movement of water for a given area of land during a selected time interval (McPherson 1973).

For a catchment area, the water balance was described in general terms by Mitchell et al. (2003) as follows:

$$\Delta S = (P + I) - (E_a + R_s + R_w) \tag{1.1}$$

Where ΔS is the change in catchment storage, including water held in the soil profile, groundwater aquifers, and natural and constructed surface water storages; P is precipitation; I is imported water; E_a is actual evapotranspiration; R_s is stormwater runoff; and R_w is wastewater discharge. Equation 1.1 is focused on the hydrological performance of the catchment area and thus it is not best suited for characterizing the water flow through cities. The law of mass conservation of Antoine Lavoisier says that in a closed system the sum of inputs equals the sum of outputs plus the change in stock. Combining this principle with Equation 1.1 and with the knowledge of the water flows in an urban environment, the balance of water in a city can be expressed as shown in Eq. 1.2. The boundaries of the material balance in Eq. 1.2 are those of the urban infrastructure and exclude the soil and the water bodies around the city (river, groundwater, lake).

$$\begin{aligned}\Sigma Import_{Public} + \Sigma Import_{Private} + \Sigma Import_{Natural} = \\ \Sigma Eva + \Sigma Export_{DirDis} + \Sigma Export_{DiffDis} + \Delta Tanks + \Delta Products\end{aligned} \tag{1.2}$$

In Eq. 1.2, $Import_{Public}$ represents the water supply through public organisations, $Import_{Private}$ represents the water supply through private abstraction facilities and $Import_{Natural}$ represents the water imports originating from natural phenomena (e.g. rain). Eva stands for flows of evaporation and evapotranspiration, $Export_{DirDis}$ represents direct discharge of water and wastewater and $Export_{DiffDis}$ represents all diffuse discharges of water and wastewater. $Tanks$

represents the water inside man-made reservoirs (including those for rain harvesting purposes if existent) and *Products* represents the water contained in food or manufactured products.

There are numerous studies showing how a mass balancing approach can be useful for evaluating WWMS. For example, Herrmann and Klaus (1997) applied this principle to evaluate the sources and pathways of water, nitrogen and phosphorus in urban drainage systems and obtained valuable information on the per capita contribution of such materials to the sewer and on their flow paths. The boundaries of this material balance were those of a household. Wolf et al. (2007) quantified the mass flows from urban drainage systems to the soil-aquifer system. For the quantification of the mass flows from urban drainage, a chain of different models were applied describing and linking urban water supply, urban drainage (including leakages), the unsaturated zone and urban groundwater systems. The boundaries of this research included the urban footprint and the aquifer beneath the city investigated in the case study. The result was a holistic description of the urban water cycle in Rastatt (Germany). Kenway et al. (2011) established an urban water balance of four Australian cities. The boundaries applied to this research corresponded to the urban footprint (from above the roofline and tree canopy to a depth of 1 meter (m) below ground). The results obtained provided a baseline to assess future changes in these Australian cities.

Martinez et al. (2011) prepared a total urban water cycle model for a Mexican city in the arid region of the country. The focus was on water supply sources management. They used an urban water and contaminant balance model with daily time steps, simulating an integrated urban water system in the city of San Luis Potosí. This is known as the Urban Water Quality (UVQ) model (Mitchell and Diaper 2005). The research results recognized that poor data availability and quality in developing countries might limit the use of such tools for holistic evaluations. However, the results of the case study also demonstrated that key requirements for an integral evaluation can still be met.

The numerous examples in literature show that a specific approach can be more or less appropriate depending on the pursued objectives and the specific conditions of a location. It also depends on the desired extent of the evaluation in terms of processes to be included, spacial boundaries and temporal limits. The available data, material and personal resources play also an important role in the selection of a methodology for the integral evaluation of any system. Possible approaches range from simple methods, collecting the information on indicators of different categories and comparing them to the applicable standards to complex and data-intensive mathematical models of whole water basins or whole countries.

In order to make a correct and complete water balance, there are numerous flows that need to be identified and quantified and there are some models including softwares available which were particularly developed to establish integral urban water balances. Mitchell and Diaper (2005) prepared a list of existing urban water and contaminant models and evaluated them. They concluded that few of the studied models included all the elements of the WWMS and that only few of them were capable of tracking water borne contaminants within the existing urban environment in detail. Later on they developed the open-source UVQ model in collaboration with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia. However, the large number of processes included in the model requires more than a hundred different predefined input parameters. The large data requirements and the lack of flexibility to freely re-design or adapt the system or model, is probably a barrier for its implementation in Mexico at locations where information is scarce.

To prepare an integral system analysis from scratch, the methodology of Material Flow Analysis (MFA) can be of great use since it allows to freely design a model for any system according to the specific needs and available information. By means of MFA, the WWMS of Mexican cities can be evaluated in an integral manner, achieving a better understanding of the water metabolism in those cities.

1.4 Material Flow Analysis

Material Flow Analysis is an evaluation method which allows the accounting of materials entering and leaving a specific process, activity or geographic region. According to the definition stated by Brunner and Rechberger (2004), MFA is *"a systematic assessment of the flows and stocks of materials within a system defined in space and time"*. The MFA methodology helps to assess the relevant mass flows and stocks of a given system in quantitative terms. It reduces the complexity of the system as far as possible while still guaranteeing a basis for sound decision making (Brunner and Rechberger 2004). MFA can be helpful in making decisions since it identifies the "bottle necks" of the system and the appropriate control and monitoring points. The depletion or accumulation of material stocks is also identified. With this, it also helps in the search for new and better systems (Espinosa Gutiérrez and Gonzalez-Blanch 2006).

MFA has been used in the past as a tool for the integral evaluation of material flows in different contexts and at different geographic locations. An extensive comparison of MFA applications around the world was made by Bao et al. (2010). The results of their investigation show that MFA applications range from national to regional level and vary widely in scope. By means of MFA the flow of wood, stainless steel, carbon, food, nutrients, fossil fuels and many other materials and substances has been calculated for numerous locations.

MFA has been used in developed countries for the partial or complete evaluation of urban WWMS and for the simulation of improvement measures (Baccini and Bader 1996, Hellström et al. 2000, Benedetti et al. 2006, Meinzinger 2010, Yoshida et al. 2013). Also in developing countries, where the access to data might be difficult, MFA has been proved to be useful (Binder et al. 1997, Belevi 2002, Huang et al. 2007, Montangero 2007, Montangero et al. 2007, Montangero and Belevi 2008, Meinzinger et al. 2009). Yacob (2008) studied the use of MFA for supporting enhanced water policy and concluded that the environmental and resource accounting indicators derived from MFA are particularly valuable for policy making.

Decker et al. (2000) recognized in their research that, in terms of weight, water flows represent the largest material flows in urban ecosystems by far. However, according to the research, the water flows through megacities (such as Mexico city) are poorly documented, although they are the largest consumables in cities along with food and fuel. The documentation in smaller cities is not expected to be any better. Apart from the research by Martinez et al. (2011), the practical application of complete mass balancing approaches for the evaluation of the WWMS in Mexican cities remains largely unexplored. Complete balances of water and pollutants for Mexican cities are rarely found in literature or they are only partially achieved.

Life Cycle Assessment (LCA), which is another methodology for assessing material flows, could be mistakenly confused with MFA, but they differ as much as they have different goals. LCA is a type of Material Flow Analysis that focuses on a specific element or substance tracing it from raw material extraction to final disposal in order to relate environmental impacts to each process or product in the chain. MFA focuses on the assessment of a region, process or activities and of all the different element flows inside the location, identifying the inflows, transformation points, the stocks being built up and the outflows. It does not necessarily include the "cradle-to-crave" principle (Espinosa Gutiérrez and Gonzalez-Blanch 2006).

1.4.1 General procedure for Material Flow Analysis

This section describes in general the practical procedure for performing an MFA based on Baccini and Bader (1996), Brunner and Rechberger (2004), Espinosa Gutiérrez and Gonzalez-Blanch (2006), Montangero (2007) and Rechberger and Laner (2011). The following terms are fundamental in MFA:

Substance This term refers to chemical elements or compounds made only of uniform units. For example: nitrogen (N) and phosphorous (P) and pure water (H_2O).

Good This term is used to refer to merchandise or materials valued economically in a positive or negative sense. A good is composed of several substances (elements and compounds). For example: drinking water, fuels, solid waste, rain).

Material The term material is used in the literature to refer altogether to substances or goods. In this study, the term "materials" is only used as synonym for goods.

Process Refers to any activity that provides (reservoirs), transforms, transports or stores (sinks) materials. Usually a process may consist of different sub-processes or steps. To facilitate the analysis, processes are often represented as "black boxes" with only its inputs and outputs being of interest. Examples of urban processes are: water supply, sewer (wastewater transportation) and wastewater treatment.

Flows They are defined as the links between the processes and represent the mass of materials flowing from one process to another in terms of mass per time. If the flow is expressed in terms of mass per time per inhabitant or per "cross section" (area) it receives the name of flux or specific flow.

Stock The total amount of materials stored in a process.

System A system is the group of processes and flows of materials which are object of the study. It is delimited by spatial and temporal boundaries. A system might be e.g. a household, a city, a region or a nation.

Boundaries are spatial and temporal. In the spatial sense they define the geographical area to be studied. The temporal boundaries define the time that the MFA has to consider in the calculations, for example: 1 day, 1 month, 1 year.

The main symbols used in MFA diagrams are shown in Figure 1.3. Usually the boundaries of a system are geographically well defined zones which coincide with political divisions such as cities, municipalities and countries. This is because data collection is easier in this way given that there are governmental institutions collecting data on that level.

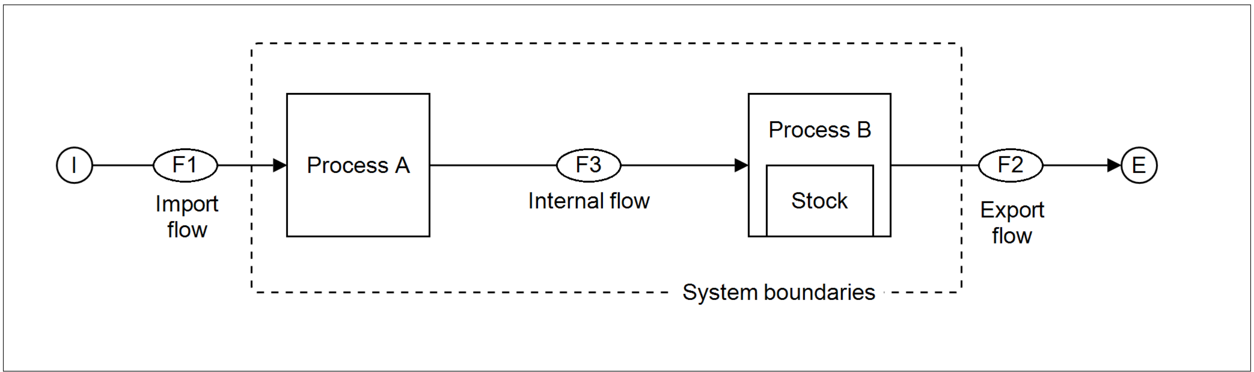

Figure 1.3: Main elements of an MFA diagram
I = Import, E = Export

Procedure

There is consensus between MFA leading experts that an MFA should start with a system analysis. The system analysis defines the system boundaries in terms of materials and substances to be analysed and in terms of temporal and spatial limits. The system definition determines the processes and flows to be included in the model as well. The boundaries of the system should be selected to guarantee the fulfilment of the research goals while keeping the system manageable in terms of data collection and complexity. The general steps for an MFA are:

1. Selection of the goods and substances to be evaluated. This is determined by the scope of the project or by the purpose of the MFA. Legal requirements and existent regulations may also influence the selection of substances.
2. Selection of processes, flows and stocks to be included in the MFA. This closely correlates to the selection of goods and substances.
3. Selection of appropriate system boundaries. The spatial boundaries must include all the processes and flows of interest. The temporal boundaries should be chosen according to the project objective: long time frames allow to balance temporary unsteadiness of the system and are well suited to obtain average values. If more precision is desired, then short periods of time allow for the detection of short term anomalies and calculating non-linear flows.
4. Evaluation of the mass flows and measurement of the changes in the substance stocks. This is done in three stages:
    (a) Preliminary rough balance of goods. If the inputs and outputs do not balance approximately, there are perhaps some flows or processes missing in the system. In this case, step 2 and 3 have to be repeated until the balance is achieved.
    (b) Assessment of the substance flows or assessment of the concentration of substances in the goods flows.
    (c) Assessment of total material flows and stocks. This is the final goal of the MFA and it is done using the mass flows of goods and the concentration of the selected substances in these flows.
5. Interpretation and presentation of results. This is definitely a crucial step of the MFA since it is the basis for decision making. At this point, the mistakes and uncertainties from the procedures have a large influence on the interpretation of results. Key aspects of the presentation of results are transparency and reproducibility. Results must be easy to understand and units must be equivalent for a better understanding.

The procedure of MFA is rather simple in principle, but it is hard to carry out with precision given that the information might not be easily available and some data might be missing. Therefore, additional core tasks of MFA are the collection, evaluation and handling of data.

The procedure for performing an MFA is illustrated in Figure 1.4. In this figure, the iterative nature of the process is clearly visible. Brunner (2004) recommends to start with rough estimations and provisional data and subsequently to refine and improve the MFA. According to Montangero (2007), the iterative procedure can reduce the costs of the MFA because determining all parameters experimentally is not possible in most of the cases. Thus, a first rough MFA helps as a basis to detect missing information and to identify the most sensitive parameters. With this information in hand, it is easier to determine which parameters should be assessed more accurately and thus the budget is used in a more meaningful and effective manner.

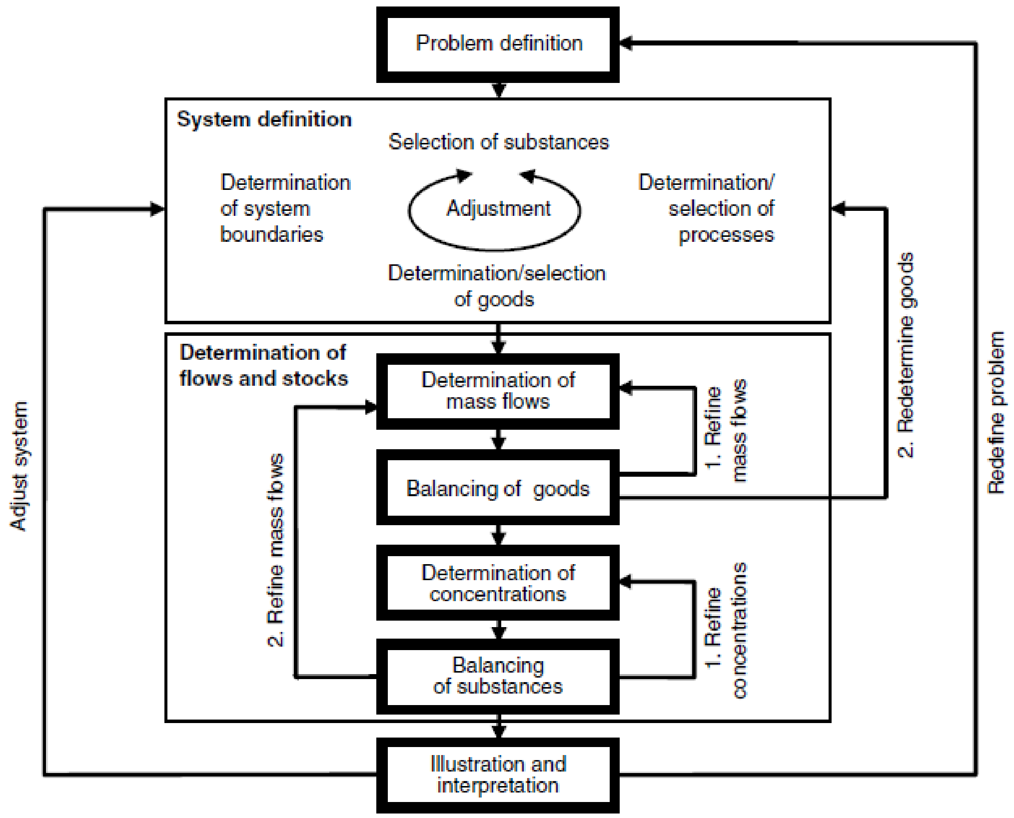

Figure 1.4: General procedure for an MFA
Source: Brunner and Rechberger 2004

Handling of data uncertainty

The information gathered for an MFA can originate from archive information, from a bibliographic research or from experiments, measurements and analysis.

When collecting information from archives or bibliographic sources, there will be probably several sources reporting different numbers or quantities according to the year, source, method or special considerations used for measurement or data acquaintance. When experiments are carried out, there is always an error margin and for several measurements there is a range of possible "true" values.

In all cases there will be an extent of uncertainty in the reported values that will lead to a certain degree of reliability on the results of the MFA. This is called data uncertainty. It can be chosen to work only with average values. However, especially in large complex systems, there is a risk that the values used will not lead to a balance. Working with probability distributions allows considering the whole range of "true values" for the flows and helps in closing the balances. Besides, it allows for a better interpretation of results. Thus, dealing with the uncertainty of the collected data is an inalienable part of a correct MFA.

Uncertainty of input information. In the case of experimental results, optimally there will be many measurements. The data can be characterized by means of a statistical analysis and its uncertainty is calculated by the so-called "frequentist view" of probability. A statistical analysis will determine the distribution type, the mean value, and the standard deviation among other important parameters. For normally distributed data, the mean value and standard deviation are appropriate to characterize the real value. For a skewed distribution, the median value and the inter-percentiles can be used to describe the whole data set in a better manner.

In many cases, it is not possible to obtain data from measurements or there are only a few measurements available. In case of limited data availability, the probability distribution has to be assumed on the basis of knowledge on each parameter (subjectivist view). In these cases, the uncertainty can be assessed by evaluating the source or the context of the information. According to the subjectivist (or bayesian) view, *"the probability of an event is the degree of belief that a person has that it will occur, given all the relevant information currently known to that person. Thus the probability is a function not only of the event but of the state of information"* (Morgan 1990). In other words, to assess the uncertainty in case of limited data availability, an "educated guess" can be made. The method of "expert judgement elicitation" is a promising method to obtain educated assumptions.

In general, to obtain better results in an MFA, it is important to describe the input parameters as probability distributions with a central value with positive and negative deviations instead of single values and it is always better to enter at least an assumed uncertainty value based on the expert's opinion than no uncertainty at all.

Uncertainty of calculated values. When using uncertain data to calculate a flow, the result will be a number with a degree of reliability directly proportional to the reliability of the source from which it was calculated. This is called error propagation. There are several ways to propagate errors in an MFA. Two of them are:

- **Gauss's law of error propagation.** If an unknown quantity is to be calculated from a function of normally distributed variables, its uncertainty (variance) can be calculated by the law of error propagation. To use this method, the random variables have to be normally distributed, and the uncertainties have to be small.

- **Monte Carlo Simulation.** This method is used when the data are not normally distributed or when the deviations are too large. The statistical distribution of the input parameters is assumed to be known and a computer algorithm is used to create random numbers according to the specified distributions. These numbers are then used to calculate the result of a function. If enough repetitions are carried out, for example 1,000 times, then 1,000 possible results are obtained and then the probability distribution of the result can be calculated. This method is well suited for calculating systems in which the input parameters differ from normal distribution but it is also very time consuming (Brunner and Rechberger 2004).

1.4.2 Software for Material Flow Analysis

To perform an MFA the use of computer software is advisable. This will facilitate the calculations and allows for an easier scenario construction and replication. This will in turn save time and costs. For very simple systems, the use of standard calculating programs such as Excel is sufficient. For complex systems, such as those representing a whole city, the use of specialized software is recommended. The decision of using a specific software depends on the characteristics of the MFA itself and on the further use of the results.

Among the software developed specifically for MFA we find for example, the Software STofflussANalyse (STAN) developed by the Vienna University of Technology, or the Swedish MFA application for water management URWARE, and the software SIMBOX developed by EAWAG (Switzerland). Additionally, some software designed for LCA (e.g. GaBi and Umberto) are suitable for MFA calculations. More MFA tools suitable for urban environments can be found in the work of Terekhanova et al. (2012) who carried out an extensive comparison of available MFA tools which could be used for purposes of Integrated Water Resources Management and which considered the urban system inputs.

1.5 Aim and structure of this thesis

The integral evaluation of WWMS in Mexican cities is essential for a realistic assessment of their performance. The goal of this thesis is to contribute to the understanding of the water metabolism in Mexican cities and to the development of integral improvement strategies. Three objectives have been chosen to reach this goal:

Obj. 1: To carry out an integral evaluation of the WWMS within a case study for a particular city.

Obj. 2: To use the integral evaluation as a basis to suggest improvement options in the city.

Obj. 3: To test the application of the integral approach for supporting urban water management in Mexico by means of a holistic evaluation of the suggested improvement options.

The city of Tepic in Mexico was chosen as location for the case study. For the integral evaluation of the WWMS of the city, the flows of drinking water, rain water and wastewater were analysed. Besides, the nitrogen (N) and phosphorus (P) loads of those flows was evaluated, since its concentration in water and waste water can be an indicator of environmental pollution. These nutrients were also used to identify pollutant sources and paths in the system.

The thesis is structured according to the timely development of the research. After explaining the methodical baseline of MFA in this chapter, in Chapter 2 the specific methodology followed for the integral evaluation of the city of Tepic is explained. The general description of the case study location and the first findings about the drinking water and wastewater system in the city are found in Chapter 3.

Chapter 4 describes how the model of the WWMS in Tepic was constructed and it explains the processes and flows included in the evaluation. The boundaries applied to the system are also explained in this chapter. The input data for three scenarios representing years 2007, 2011 and 2030 is also presented in detail in this chapter followed by the results of these evaluations. The chapter ends with a plausibility analysis and the conclusions from these first evaluations.

A second more detailed and data-intensive evaluation was carried out for the dry and rainy seasons in year 2011. The approach considered for these scenarios and the results of this detailed evaluation are presented in Chapter 5. This chapter contains the final results of the integral evaluation to the WWMS of Tepic.

Based on the final results of the integral evaluation, Chapter 6 explains the approach chosen for the detailed projections of the situation in year 2030, which also included the dry and rainy seasons. This chapter includes the evaluation of the potential future challenges for the WWMS of the city. At this state, a sensitivity analysis was carried out for the criteria identified as relevant in terms of water use and sewer performance, and it revealed the key change drivers for effective improvements in the WWMS in Tepic.

Chapter 7 describes the improvement options suggested for the city based on the performed integral assessments and on the discovered key change drivers. The implementation impacts of the suggested improvements are evaluated in a holistic manner in this chapter.

In Chapter 8, the benefits and challenges for the application of integral approaches in the evaluation of WWMS in Mexican cities is discussed. This chapter summarizes the main results of the evaluation in Tepic and discusses the lessons learned from the research.

Chapter 2

Methodology

2.1 Thesis procedure

Based on the MFA methodology described in the previous section, on the project characteristics and on the desired outcomes, an overall procedure was defined (Figure 2.1). Three phases are distinguished in the research time line:

Phase. I: The first phase of the research began with a site visit. The main goal during the first site visit was gaining project partners, gathering first-hand information and collecting data. With the collected information, a system analysis was carried out and a model representing the WWMS of the city was prepared. Using the created model, a preliminary MFA of three basic scenarios representing years 2007, 2011 and 2030 was carried out (details about the definition of the scenarios are found in Chapter 4).

Phase. II: In the second phase of the project, the preliminary MFA results were discussed with the project partners (during a second site visit). Based on the discussion, adjustments were made to the model allowing for a first complete MFA of all prepared scenarios. Later in this phase, a plausibility test of the results identified the improvement needs of the model and a measurement campaign was realised in the city of Tepic to gather more detailed information about the domestic wastewater flows.

Phase. III: In the third phase of the project, the information gathered during the measurement campaign was implemented to the model and a detailed MFA of the scenarios 2011 and 2030 was completed. The results of the integral evaluation were shared with the project partners during a third site visit. These results were also used as basis to elaborate improvement options according to the specific characteristics of the city.

The following sections provide further details about the procedure of this research. Furthermore, several additional investigation tasks were carried in parallel during the whole research duration to explore potential improvement options for the city. A complete list of these parallel investigation tasks is included in Annex C. The objectives and methodology for each investigation tasks are found in the separated reports. Their outcomes were integrated in this thesis in the third phase of the research (Chapter 7).

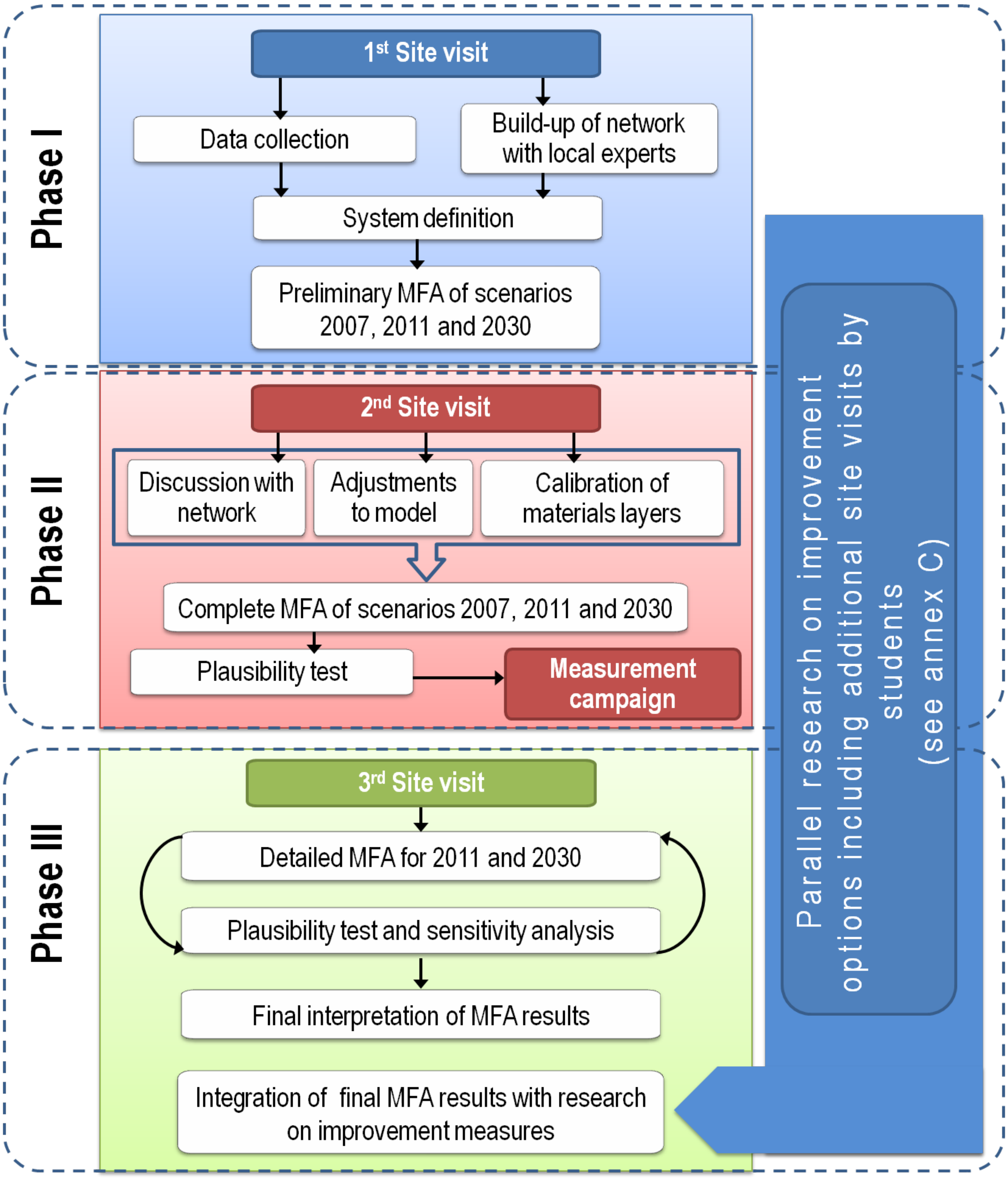

Figure 2.1: Thesis procedure

2.2 Relevant organisations involved in the research

The present research was founded by the the program for International Postgraduate Studies in Water Technologies (IPSWaT) of the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF). At the beginning of the research, a network of local experts was set up in Tepic. The project network was mainly composed of experts from following local institutions:

- Public Water Supply and Sewer Works (*Sistema de Agua Potable y Alcantarillado*, SIAPA Tepic).
- State representation of the Mexican Water Commission (*Comisión Nacional del Agua en Nayarit*, CONAGUA Nayarit).
- Department of basic sciences and engineering of the university of Nayarit (*Universidad Autónoma de Nayarit, Unidad Académica de Ciencias Básicas e Ingenierías*, UAN-ACBI).
- Department of social sciences and humanities of the university of Nayarit (*Universidad Autónoma de Nayarit, Centro Universitario de Ciencias Sociales y Humanidades, UAN- CUCSH*)
- City council (*Ayuntamiento de la ciudad de Tepic*).

In the course of the research, contacts with experts from further organizations were created and provided with a valuable input to specific research tasks, such as modelling or applicability of improvement options. These further organizations were:

- Institute for Water Quality, Resource and Waste Management of the Vienna University of Technology (TU-Wien)
- Mexican Institute of Water Technology (Instituto Mexicano de Tecnología del Agua, IMTA)
- Autonomous University of Chihuahua (Universidad Autónoma de Chihuahua, UACH)

Furthermore, a constant scientific exchange took place with other doctoral students from the IPSWaT program. This scientific exchange also provided with valuable inputs and insights for the research.

2.3 Site visits and data collection

Three site visits to Tepic were carried out during the research. The site visits took place in November 2010, December 2011-January 2012 and in June 2013. Additional site visits by supervised students took place during June-October 2011 (Evers 2011) and during April-May 2014 (Lafratta 2014, Lafratta et al. 2014).

During the on-site periods, data was collected by means of visits to installations, observations in several neighbourhoods, document review and interviews. Additionally, meetings with the project partners took place for the discussion of data and results. Photos of the site visits can be found in Annex B.

The project partners enabled the access to installations such as pumping stations, laboratories of water quality, sewer inspection pits and wastewater treatment plants. They also provided archive material containing information about the water and wastewater infrastructure in the city and collaborated during interviews about these topics. The most relevant documents obtained from the project partners are listed below:

- Assessment of the wastewater infrastructure carried out in 2000.
- Assessment and integral planning of water and wastewater infrastructure carried out in 2007.
- Technical drawings of the drinking water and wastewater infrastructure of the city for the period 2000-2010.
- Volume measurements of the groundwater wells.
- Design documents of all the wastewater treatment plants.
- Results of continuous drinking water monitoring and of single wastewater analysis.

The data obtained from the documents was complemented with the on-site observations and with expert consultation as well as with literature data in order to complete the data requirements of the MFA.

2.4 System definition

To evaluate the WWMS in Tepic, it is necessary to analyse the drinking water and the wastewater flows of the system at a material level. The flows of rain water are also relevant: the rain can enter the wastewater sewer and transfer pollutants from the sealed surfaces thus affecting the quantity and composition of the wastewater. To obtain information about the water quality in the system, it was decided to expand the MFA and include the analysis of nitrogen and phosphorus content of the flows (substance layers of the model). These are the only two chemical parameters included in the list of basic pollutants of the Mexican guideline NOM-001-SEMARNAT-1996 (SEMARNAT 1997) which regulates the minimum requirements for the discharge of wastewater into water bodies. These nutrients are used to recognize pollutant sources and paths in the system.

The processes that are included in the system boundaries of an MFA must reflect the whole chain of actions for the provision of a certain service (Meinzinger 2010). In this study, the services in question are the supply of drinking water and the management of wastewater (collection and treatment). These services are crosslinked via the consumers of the drinking water which are simultaneously the wastewater generators. A rain[1] event can impact the wastewater collection system even when separated sewers are in place and thus they should be included in the analysis. The following list summarizes the processes included inside the system boundaries:

1. Water supply
2. Water use
3. Wastewater collection
4. Wastewater treatment
5. Stormwater catchment
6. Stormwater collection

2.5 Software choice

The software selected for the MFA in this research was STAN. Besides the proven technical robustness and flexibility of the software, its user friendliness played a major role in the decision. In STAN the elements required for the MFA (such as processes, flows and system boundaries) are graphically created in the program. The graphically created model is automatically translated in the background in a mathematical model. STAN works by means of four types of equations: balance equations, transfer coefficient equations, concentration equations and stock equations. Additionally, the program allows the user to create customized linear equations to represent relationships between the system elements and for the automatic calculation of interdependent flows. However, model equations required for the calculation of input flows (parameters) must be created and evaluated outside STAN.

[1] A clear differentiation between rain and stormwater was made in this thesis: *rain water* is found in the atmosphere only. As soon as it touches the surface, rain water is considered to be *stormwater*.

The creation of a system and its equation system by means of the graphical interface in STAN allows to focus on the creation of the model and on the data collection and makes the program more accessible and understandable for less specialized users. Furthermore, as a freeware it may improve the acceptance amongst stakeholders and it could facilitate the communication and dissemination of the model and its results. Further advantages of the model are the possibility of using redundant information to improve uncertain data by embedded data reconciliation procedures. An integrated error propagation algorithm according to the Gaussian principle is also included so that an additional Monte Carlo simulation is not necessary. According to the empirical rule for normal distribution, this implies a confidence interval of 67% for the results, provided that the assumption of normal distribution in the input parameters is valid. More details on the software can be found in Cencic and Rechberger (2008) and on the official webpage of the software (http:\www.stan2web.net).

Chapter 3

Case study location

3.1 General information

The city of Tepic is the capital city of the federal state of Nayarit and it is located in the western part of Mexico (Figure 3.1). The city has a population of 332,863 inhabitants according to the last census in 2010 (INEGI 2012). It is one of the 200 urban middle sized settlements[1] in which 36% of the Mexican population in the country lived by 2010. The remainder lives in smaller urban or rural settlements (50% of total population) or in one of the 11 large Mexican cities (14% of total population)(Consejo Nacional de Población 2008).

Tepic lies 920 meters above sea level. It has a warm sub-humid climate and the average temperature is 21.6 ° C. The average yearly rainfall is 1079 mm and most of the rain falls from June to September (INEGI 2013). The evapotranspiration rate is about 800 mm a^{-1} (INEGI 2011).

The most important industrial activities in the city are sugar production from sugar cane and cigarettes production. The production of soft drinks together with other food processing activities such as production of snacks, dairy and meat products are also relevant local industrial activities (H. XXXIX. Ayuntamiento de la ciudad de Tepic 2012, INEGI 2014). The contribution of the whole federal state of Nayarit to the national Gross Domestic Product (GDP) is less than 1% and it is heavily based on the services sector (71% of total contribution) (INEGI 2014).

[1] Urban settlements are defined as locations with 15,000 inhabitants or more. A settlement is considered as middle sized when its population is 100,000 to 1 Mio. inhabitants (Consejo Nacional de Población 2009).

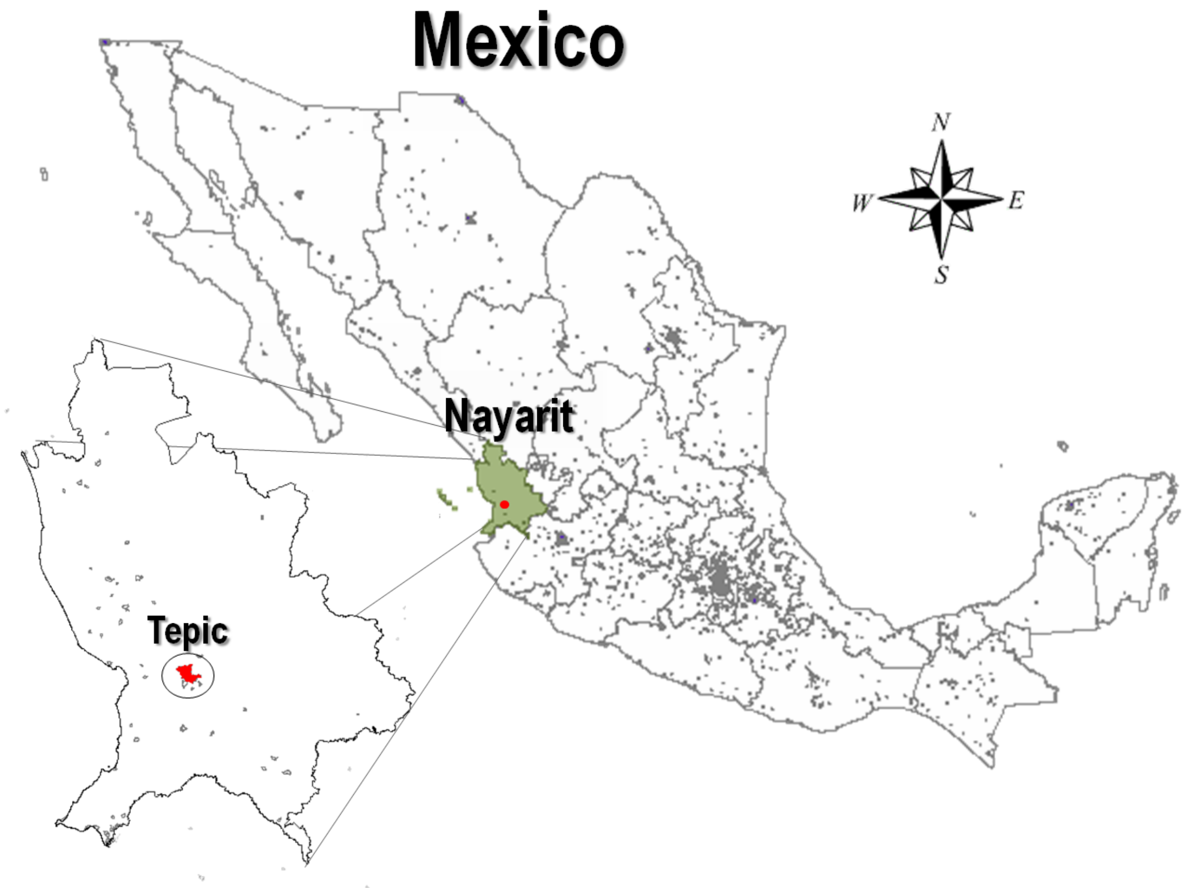

Figure 3.1: Location of Tepic

3.2 Drinking water and related infrastructure

The city of Tepic relies on groundwater sources for its drinking water supply. The abstraction of groundwater, its conditioning and the distribution of the drinking water is carried out by SIAPA Tepic.

The water is abstracted from the aquifer *Valle de Matatipac*. This is an unconfined aquifer whose annual recharge is 124 Mio m^3. The groundwater table under the city of Tepic is 60–70 m below the surface (CONAGUA 2009). The dynamic level of the groundwater wells operating in Tepic varies between 27 m and 150 m and most of them have a dynamic level deeper than 50 m (Castillo Delgado 2007). The abstracted water is conditioned by means of disinfection (chlorination). The length of the drinking water network is 703 km. The pipelines have an average age of 19 years. The youngest pipelines are 10 years old and oldest ones up to 70 years (stand 2007, based on Castillo Delgado 2007). The general condition of the network was described as regular and water losses are present at numerous locations (SIAPA, pers.comm.).

The public drinking water service supplies 98% of all homes in the municipality. The remaining population obtains water from their neighbours or from the river Mololoa. They also buy water from water trucks of private local companies.

Furthermore, it is a common practice in all households to additionally buy bottled water for human consumption.

The registry of users of the SIAPA Tepic comprises a total of 107,787 users including homes, commerce and industry. Water consumption measurement takes place at less than 3% of users (H. XXXIX. Ayuntamiento de la ciudad de Tepic 2012). The users not equipped with volume measurement devices pay fees according to their categorization. The possible categories are: domestic user (with low, middle or high income), non-industrial/non-domestic users (includes commercial users and public services) and industrial users. The distribution of users in the registry of the SIAPA Tepic is presented in Figure 3.2. Additionally, some users operate their own groundwater wells to provide themselves with water for their activities. The Public Registry of Water Use Rights (*Registro Público de Derechos del Agua*, REPDA) indicates 68 concessions in the city of Tepic for the abstraction of groundwater for domestic, industrial and miscellaneous use as well as for the services sector (CONAGUA 2012).

The fees for water services are paid according to user classification. It was observed from the fee paid by domestic users, that 85% of the total amount corresponds to drinking water fees and 15% are charged for sewer services (state of January 2011).

In 2011 there was a delay of two or more months in the payment of 40% of the contracts for water services. Debtors include users from all categories, all neighbourhoods and all social levels. The total debt amounts to over MXN$172.5 Mio. (about €10.6 Mio.) (H. XXXIX. Ayuntamiento de la ciudad de Tepic 2012).

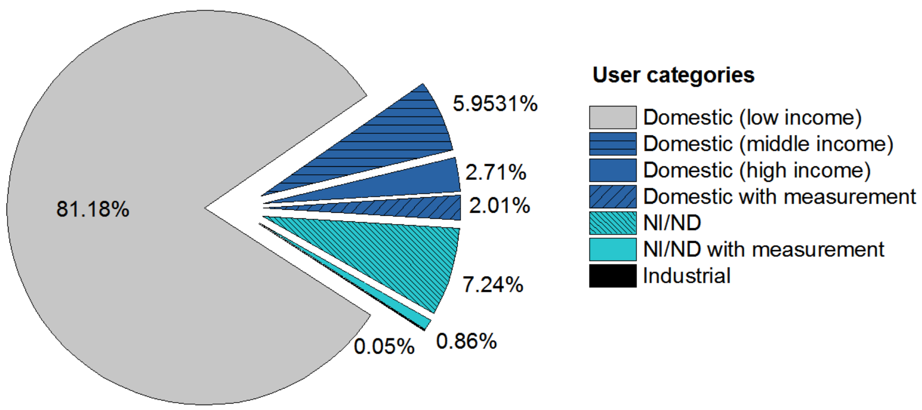

Figure 3.2: Distribution of users registered in SIAPA Tepic.
NI/ND= non-industrial/non-domestic users
Source: based on Castillo Delgado 2007, stand 2006.

3.3 Wastewater and related infrastructure

There are separated sewers for stormwater and for municipal wastewater in Tepic. The city council is in charge of the stormwater sewer and SIAPA Tepic operates the sewer collecting wastewater from households, industry, commerce and services (wastewater sewer).

The stormwater sewer collects the run-offs from the sealed surfaces of the city. A network of open channels and pipelines conducts the collected rain water towards the river *Mololoa* without previous treatment. There are several illegal discharges of wastewater to the stormwater sewer as well as erroneous connections between the stormwater sewer and the wastewater sewer so that there is a certain flow exchange between these two sewer systems. The wastewater sewer collects the wastewater of 98% of homes in the city (state of 2011). This sewer also collects wastewater of industrial and non-industrial/non-domestic users. Some of the latter have an additional permit for direct wastewater discharge to the river as well.

The age of the sewer pipelines is in average more than 40 years (state of 2009, H. XXXVIII. Ayuntamiento de Tepic 2009). Its general condition was described as good for 20% of the network, regular for 60% of the network and bad for 20% of the network (SIAPA, pers.comm.). Other sources report that 466 km of the sewer network in the city are in critical condition (state of 2012, H. XXXIX. Ayuntamiento de la ciudad de Tepic 2012). Due to the age and condition of the wastewater sewer, infiltration and exfiltration processes take place.

The wastewater sewer network is designed to conduct the collected wastewater towards one of the four Wastewater Treatment Plants (WWTPs) in the city. The wastewater overflow is by-passed to the river before entering the WWTPs. The treated wastewater is also discharged to the river. A general description of the technologies and capacities of each WWTP is presented in Table 3.1. At all WWTPs, the sludge is subjected to dewatering and drying before being disposed of at empty fields or at the local waste dump. The city recently implemented improvements in its WWMS. The past and planned improvements are summarized in Table 3.2.

Table 3.1: Description of wastewater treatment facilities in Tepic

Name of facility	Construction date and technology	Capacity (in L s^{-1})
El Punto	Installed before 2007 with primary treatment and chlorination. After upgrade in 2011, primary and secondary treatment (trickling filters) and chlorination.	Initial: 427 After upgrades: 750 (largest catchment area)
Forum	Installed in 2011. Primary and Secondary treatment (biofilm rotatory reactor) and chlorination.	100. Planned upgrade to 260 (second largest catchment area)
Delicias	Installed in 2011. Primary and secondary treatment (trickling filters) and chlorination.	100 (third largest catchment area)
La Cantera	Installed before 2007 with primary and secondary treatment (activated sludge) and chlorination.	60. Planned upgrade to 90 (smallest catchment area)

Table 3.2: Improvements in the water and wastewater management system of Tepic after 2007

Time period	General description of improvements*
2007-2011	Increased coverage of public water supply and wastewater sewer networks. Reduction of interconnections between wastewater and stormwater sewers. Reduction of illegal discharges of municipal wastewater to the stormwater sewer. Improved maintenance of manholes, drains and slabs in the wastewater sewer. Upgrade of the main wastewater treatment plant (El Punto) with secondary treatment and capacity increase from 427 L s^{-1} to 750 L s^{-1}. Construction and start of operations of wastewater treatment plant Forum. Construction of wastewater treatment plant Delicias.
Planned	Reduction of water losses from the drinking water distribution system. Further reduction of interconnections between wastewater and stormwater sewers. Further reduction of illegal discharges of municipal wastewater to the rain sewer. Further repair and continued maintenance of manholes, drains and slabs. Reduction of the direct discharge of stormwater to the wastewater sewer from house roofs and paved house yards (connection to the stormwater sewer instead). Capacity increase at wastewater treatment plant La Cantera to 90 L s^{-1}. Capacity increase at wastewater treatment plant Forum to 260 L s^{-1}. Start of operations of wastewater treatment plant Delicias.

* Description and scope of improvements as communicated by SIAPA Tepic and CONAGUA Nayarit.

Chapter 4

Basic scenarios 2007, 2011 and 2030

This chapter comprises all the research needed for the completion of the basic scenarios representing years 2007, 2011 and 2030. The approach taken to model the WWMS in Tepic is firstly explained in Section 4.1 process by process, based on the general procedure for MFA (Chapter 1) and on the knowledge gained about the drinking water and wastewater related infrastructure in the city (Chapter 3). An overview of the complete system including all processes and their interconnections is shown in Figure 4.1.

Section 4.2 continues with a detailed listing of the information used to model each scenario. Sections 4.3 to 4.5 present the results for the MFA of these basic scenarios along with the results of the plausibility analysis and the conclusions for this part of the research.

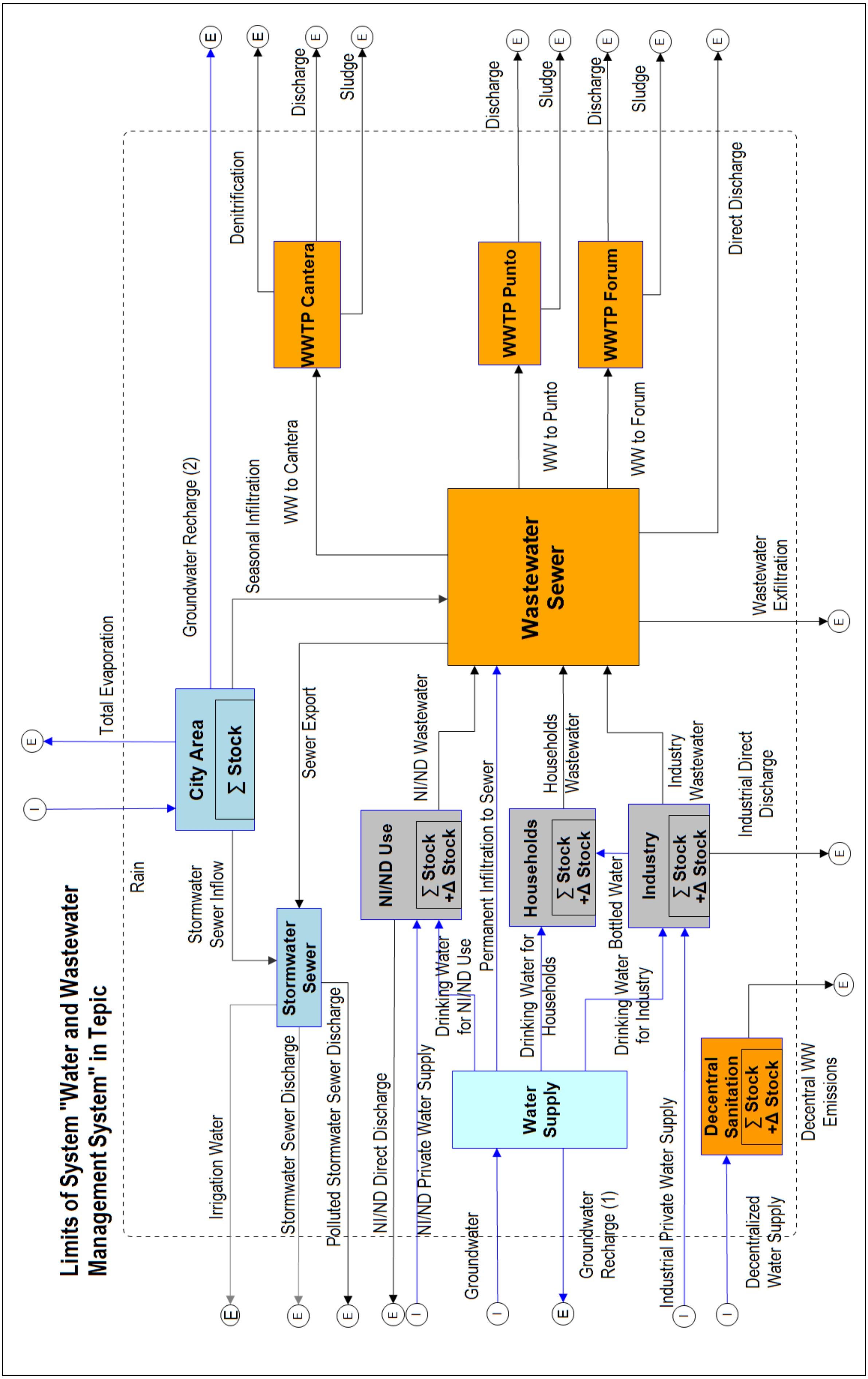

Figure 4.1: Water and Wastewater Management System in Tepic (scenario 2011).
Abbreviations: E=Export, I=Import, NI/ND=Non Industrial/Non Domestic, WW=Wastewater.

4.1 Model set up

4.1.1 Water supply

A Groundwater flow is the only input to the process Water Supply. The outputs from this process are the drinking water flows to the different users in the city.

Water Supply was modelled with two subprocesses. The first subprocess, named Water Supply Distribution, includes the abstraction and distribution of groundwater to the users. The conditioning of the groundwater for its consumption consists only of chlorination by means of an HOCl solution and it was considered that groundwater chlorination represents a negligible input of water to the system not affecting the N or the P content of the flow. For these reasons, it was not included as an additional subprocess.

The second subprocess is an Infiltration Process. Due to deterioration of the pumping equipment and of the pipeline network, there are losses in the distribution system. A fraction of the pumped groundwater is lost and it can infiltrate into the sewer network (flow Permanent Infiltration) or flow deeper into the ground reaching the aquifer (flow Groundwater Recharge (1)). The process Water Supply and its subprocesses are shown in Figure 4.2.

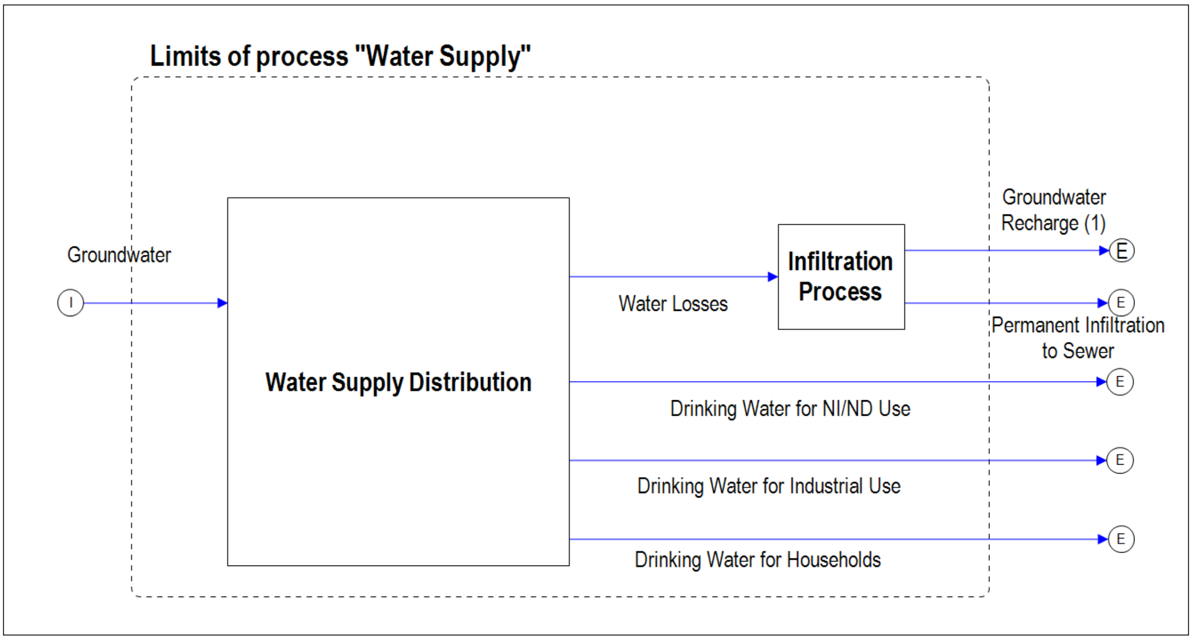

Figure 4.2: Process Water Supply.
Abbreviations: E=Export, I=Import, NI/ND=Non Industrial/Non-Domestic.

4.1.2 Water use

The water users were grouped in three categories: Households, Industry and Non-Industrial/Non-Domestic Users (NI/ND Use). Each of these users was represented as a separate process. An additional process named Decentral Sanitation was used to represent the households not connected to the water and wastewater services of the SIAPA Tepic.

The inputs to each of these processes are: drinking water flows from the Water Supply process and water flows from private sources. The private supply of water was represented in the model as an import flow to each consumer group without any further conditioning process. In the case of Households, there is an additional input of purified bottled water produced by the local industry. All drinking water required by the city was considered as provided by local public or private producers.

To simplify the model, the input of nitrogen and phosphorus from food and chemicals was represented as a flow from a reservoir inside each water use process. Food imports typically account for less than 1% of the mass balance of a city (Wolman 1965). For this reason, the water content of food and chemicals supply was considered as negligible compared to the other water imports into the city and it was not included in the simulations.

According to the Mexican guidelines for drinking water and sewer services (*Manual de Agua Potable, Alcantarillado y Saneamiento*, MAPAS), the wastewater generation is equivalent to 0.75 of the drinking water input (CONAGUA 2010). This implicates a loss of water in the system which is supposed to be lost in the processes e.g. by evaporation, gardening and car washing. It is not known how much of this water actually reaches the aquifer. Therefore it was not considered as a potential source of groundwater recharge in this study and it was indicated as a flow towards a sink inside a subprocess named Water Lost. The outputs of each of these users are flows of wastewater to the sewer or direct wastewater discharges into the river.

The process NI/ND Use and its subprocesses are shown in Figure 4.3. The processes Decentral Sanitation, Households and Industry are very similar. Special taken considerations were:

- No information was available about the city-wide average water losses in the industrial processes. Therefore, the process Industry does not include the subprocess (sink) Water Lost. It was assumed that no water accumulation in the process would take place neither.
- Both processes Households and Decentral Sanitation represent domestic use of water. Nevertheless, the process Households includes only the homes connected to the public services. Opposite to this process, the process Decentral Sanitation was used in the model to represent those homes in the city which are not connected to the public services. These homes discharge their wastewater directly to the river.

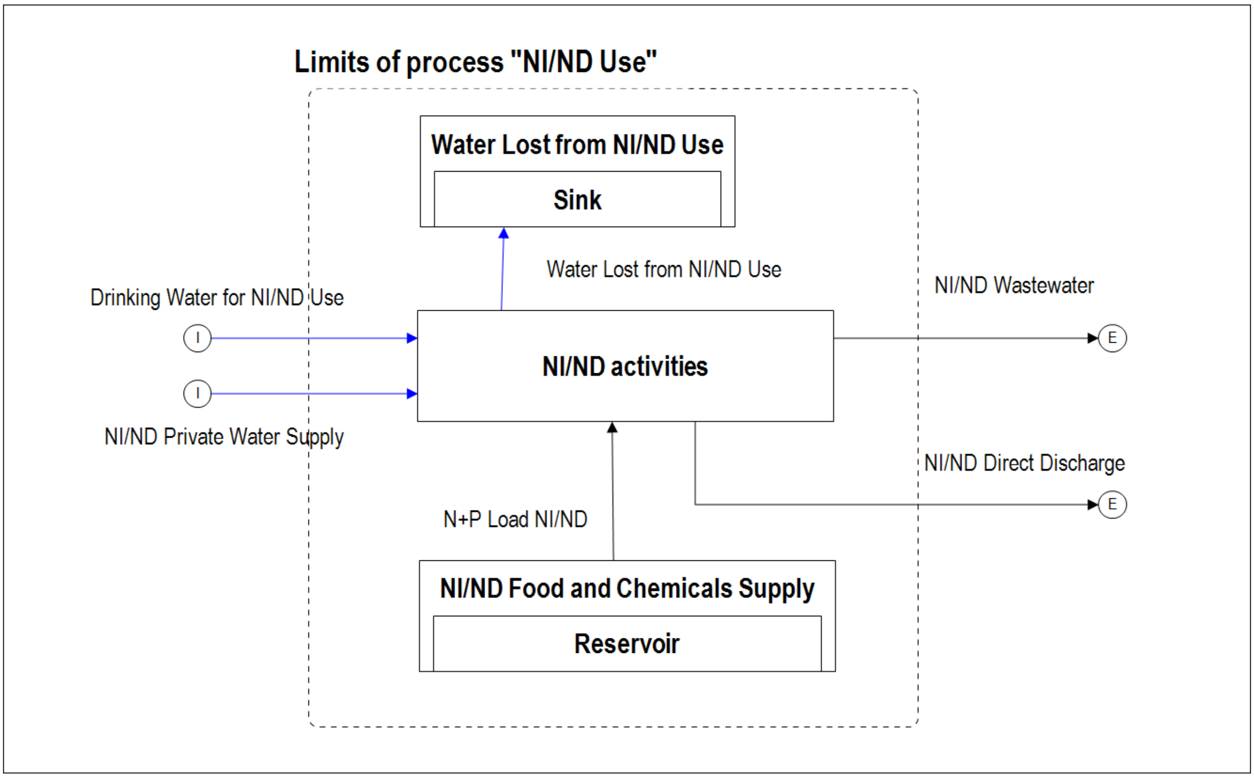

Figure 4.3: Process Non-Industrial/Non-Domestic Use Use.
Abbreviations: E=Export, I=Import, NI/ND=Non-Industrial/Non-Domestic, N+P=nitrogen and phosphorus

4.1.3 Wastewater collection

The collection and transportation of wastewater was modelled as a single process named Wastewater Sewer (WW Sewer). The inputs to this process are the flows of wastewater from the users in the city. Besides, infiltrations were included in the model as additional inputs of water. Infiltrations can originate from losses in the Water Supply process (flow Permanent Infiltration) or from stormwater (flow Seasonal Infiltration). Due to the reported low groundwater level in the city (Section 3.2) a constant infiltration of groundwater to the sewer was not included in the model at this point. However, since the groundwater level may rise due to rain events and it may then infiltrate the sewer, the groundwater infiltration was indirectly considered in the model as part of the Seasonal Infiltration flow.

The process WW Sewer has several outflows. The outflow Sewer Export represents the wastewater flow towards the stormwater sewer due to illegal discharges and to mistakes at the pipeline connections.

The outflow named Wastewater Exfiltration represents the loss of wastewater to the soil through damaged pipelines. In Tepic, the depth of the constructed sewer pipelines range from 1.25 to 2.45 m (Castillo Delgado 2007). The groundwater table in the region is found in average at a depth of 15-20 m. Deeper levels are present at the urban area of Tepic (CONAGUA 2009). This information led to the conclusion that the exfiltration can take place in both seasons ceasing only when the level of the groundwater table reaches the sewer pipelines after

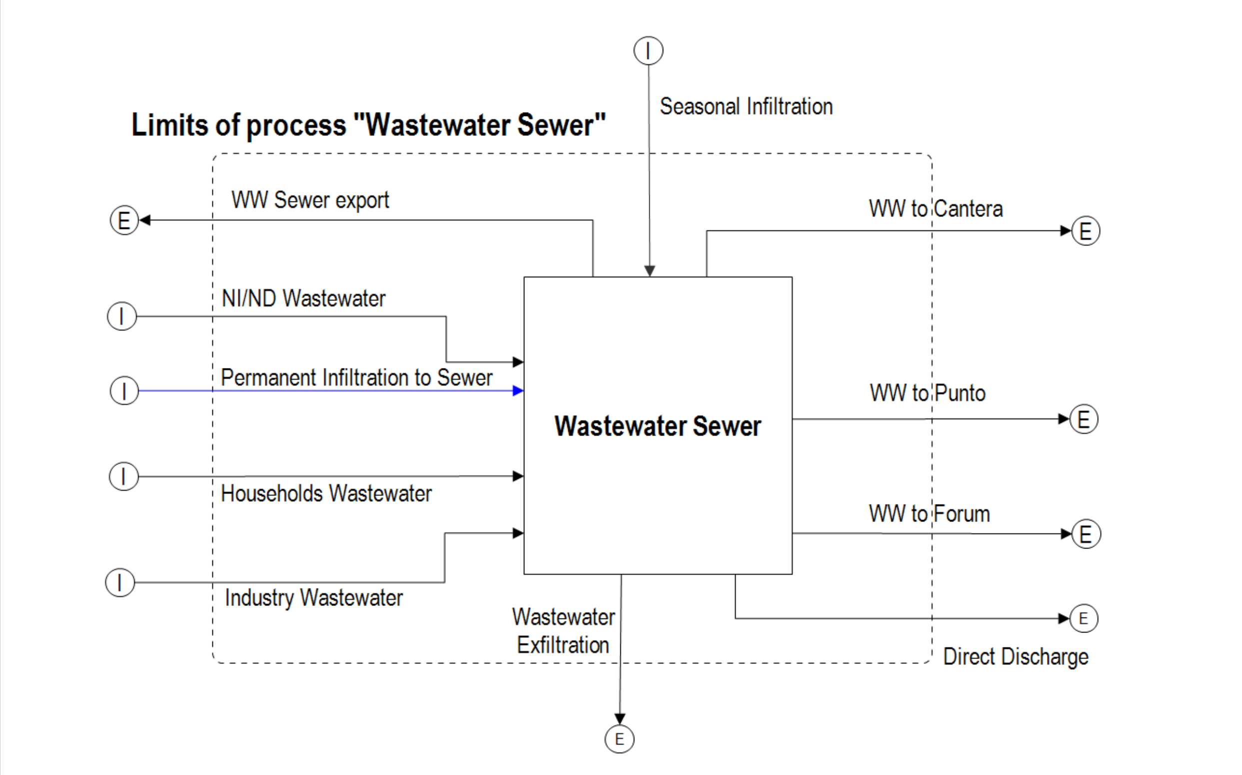

Figure 4.4: Process Wastewater Sewer (as modelled for scenario 2011).
Abbreviations: E=Export, I=Import, NI/ND=Non-Industrial/Non-Domestic, WW=Wastewater

heavy or constant rain events and recommencing as soon as the groundwater level decreases.

Further outflows of this process connect the WW Sewer with the WWTPs. It was assumed that each WWTP would receive only the wastewater volume specified in its design. All exceeding volume was represented as one single Direct Discharge to the river. The process WW Sewer is shown in Figure 4.4 as modelled for scenario 2011. In scenario 2007 the WWTP Forum did not exist yet and in scenario 2030 the WWTP Delicias is included for a total of four WWTPs in operation.

4.1.4 Wastewater treatment

The processes of wastewater treatment were represented as black boxes with input and outputs and without detailed modelling of all the treatment steps.

The inputs to the WWTPs are wastewater flows leaving the process WW Sewer. The main output of the WWTPs are flows of treated wastewater into the river (flows named Discharge). The sludge is also an output of the process. The sludge of each WWTPs is subjected to dewatering and drying before being disposed of at empty fields or at the local waste dump (the empty fields and the local waste dump are outside the boundaries of the modeled system). The evaporation of

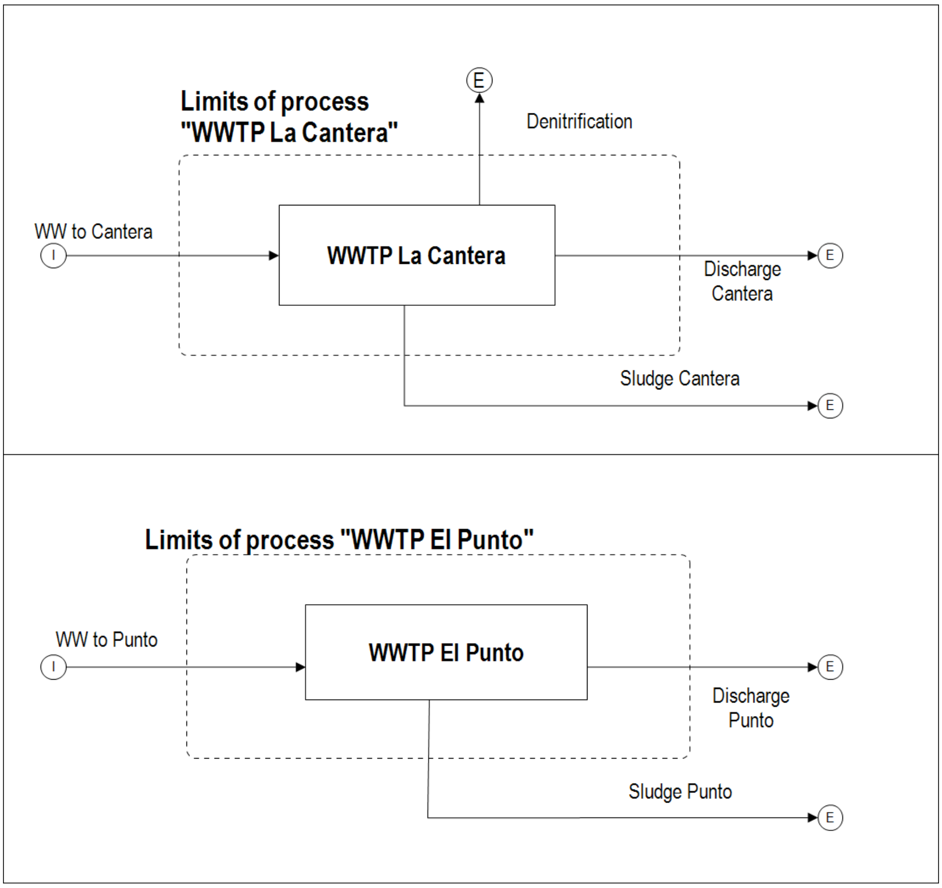

Figure 4.5: Process Wastewater Treatment for two different treatment plants.
Abbreviations: E=Export, I=Import, WW=Wastewater, WWTP=Wastewater treatment plant.

water from WWTPs is negligible in terms of mass transfer (Huang et al. 2007) and it was not considered by this model.

The information received about design, construction and operating conditions at the WWTPs allowed for a literature research of the expected denitrification at the different locations. It was established that, due to the type of treatment and its configuration, at the WWTP La Cantera some degree of denitrification could be expected. Therefore, an additional outflow was modelled at this WWTP to represent the N removal. No significant denitrification was expected at the other WWTPs and therefore, this flow was omitted. Figure 4.5 represents the modelling for the WWTP La Cantera and for the WWTP El Punto. The WWTP Forum and WWTP Delicias were modelled identical to WWTP El Punto.

4.1.5 Stormwater catchment

A process named City Area was included in the model to account for the inputs of stormwater to the city. The possible destinations of the stormwater in the city are numerous and required the application of several sub-processes which are illustrated in Figure 4.6.

The complete urban surface of the city was considered as stormwater catchment area (subprocess City Surface) and it can be divided into pervious (unsealed) and impervious (sealed) areas.

The unsealed areas were represented in the model as a process named Soil. From this process the stormwater can directly infiltrate into the ground to potentially recharge the aquifer (export flow named Groundwater Recharge (2)) or it can evaporate. When the rain events are intense or continuous, the soil becomes saturated and the groundwater level rises. The water can then infiltrate into damaged sewer pipelines as a part of the Seasonal Infiltration (Fischer 1991)

From the Sealed Areas such as streets, house roofs and paved yards, the stormwater can evaporate or it can run off towards the Soil (flow Runoff to Soil). It can also enter the WW Sewer through wrong connections or through open manholes and damaged slabs (flow House Roof Inflow and flow Other Inflows). The remaining stormwater flows into the Stormwater Sewer as a flow named Stormwater Sewer Inflow.

Similar to the water consumption processes, the input of nitrogen and phosphorus from pollution of the sealed surfaces was represented as a flow from a reservoir inside the process.

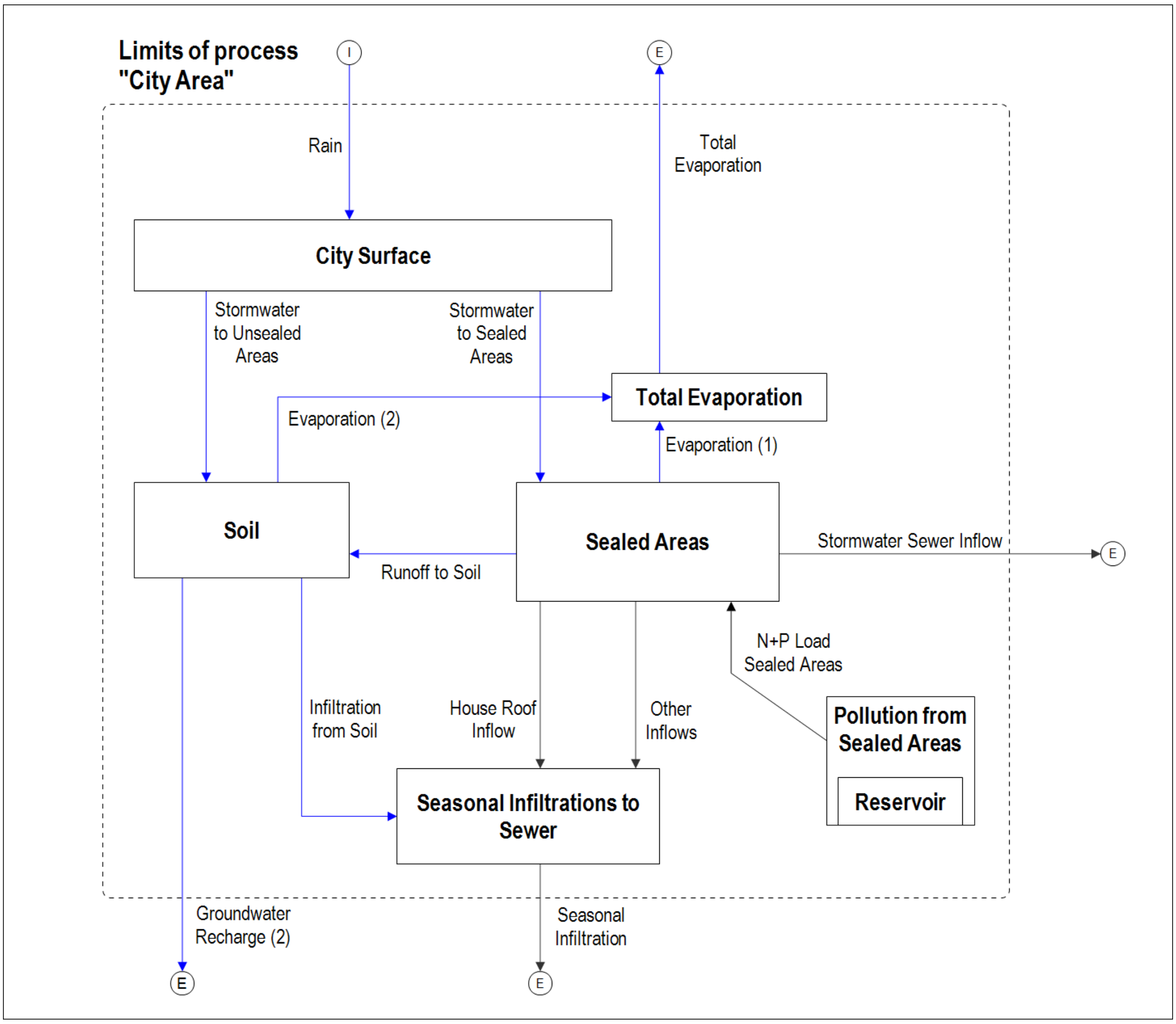

Figure 4.6: Process City Area.
Abbreviations: E=Export, I=Import, N+P=Nitrogen and Phosphorous.

4.1.6 Stormwater collection

As explained in section 3.3, Tepic counts with a separate sewer for the stormwater. A treatment of the collected stormwater does not take place. The stormwater is only collected in the stormwater sewer and is then discharged to the river or conducted to agriculture.

The process Stormwater Sewer has two inputs: one of them is the stormwater collected from the Sealed Areas in the City Area process (flow Stormwater Sewer Inflow). Due to the reported illegal discharges and to mistakes with the pipeline connections, there is an additional input of municipal wastewater from the WW Sewer process (flow Sewer Export).

Once inside the Stormwater Sewer, the stormwater has three potential fates: it is used for agriculture (Irrigation Water), it flows towards the river (Stormwater Sewer Discharge) or it is mixed with the Sewer Export and flows to the river as Polluted Stormwater Sewer Discharge. The flows and internal processes of the Stormwater Sewer are illustrated in Figure 4.7.

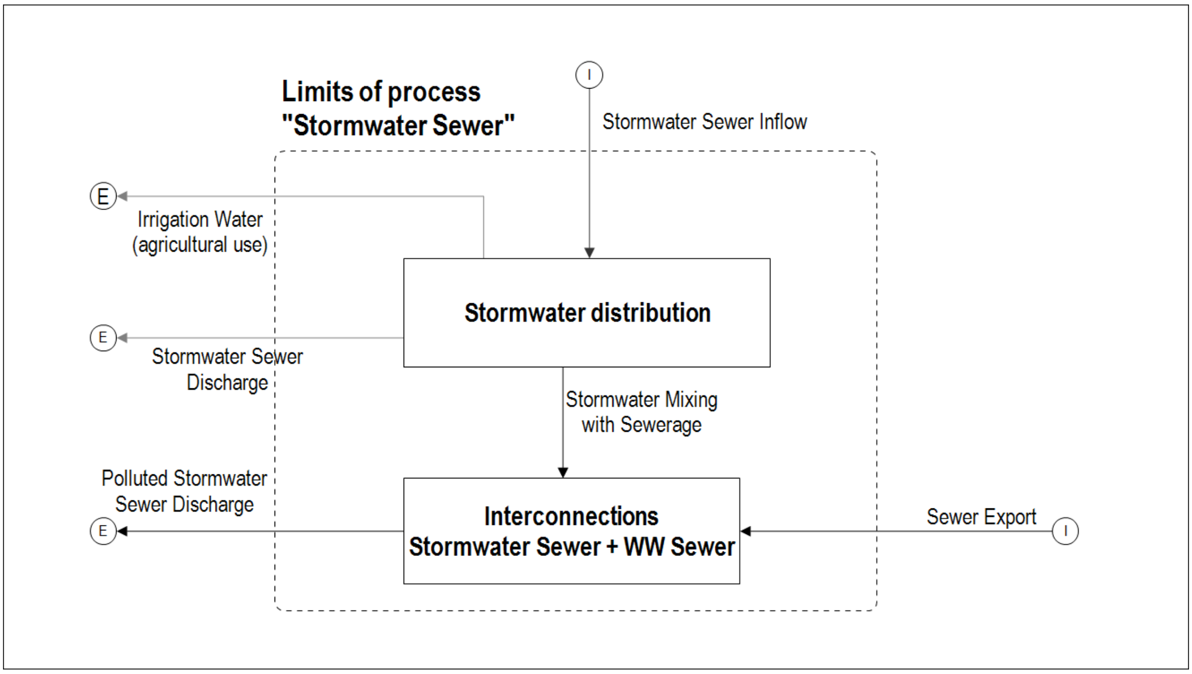

Figure 4.7: Process Rain Sewer.
Abbreviations: E=Export, I=Import, WW=Wastewater.

4.1.7 Scenarios

For the selection of the scenarios it was considered that Tepic experienced important improvements in its WWMS between years 2007 and 2011. Further improvements are planned for the years after 2011. To compare the situation in the city between years 2007 and 2011, two scenarios were necessary: scenario 2007 and scenario 2011. The year 2025 and 2030 are often used in Mexico as planning horizons. However, the MWA 2030 is currently the most important document in terms of long term strategies in the water sector and thus year 2030 was selected to establish a scenario with a first prognosis of the future situation in the city. This was named scenario 2030. These three scenarios are considered and referred to as the basic scenarios in the present research.

The basic scenarios are used to simulate the impacts of progressive improvement in the system (table 3.2) considering changing conditions in the city such as population and area growth and applicable known or expected deterioration (e.g. increase of losses in the Water Supply process). To show the impact of changes in the average precipitation on the area of the system, two further sub-scenarios for year 2030 were calculated: scenario 2030-Dry and scenario 2030-Rainy. Scenario 2030-Dry considers 50% less rain than the annual historical average and scenario 2030-Rainy considers 50% more rain. All other conditions were left as in the basic scenario 2030. The 50% change in the precipitation was chosen arbitrarily aiming to introduce a change in the scenarios large enough to allow observing significant changes in the simulation results.

The spacial limits (geographical limits) of the scenarios were placed at the urban limits of the city. The temporal limits of all scenarios were set from January 1^{st} to December 31^{st} in order to model a period of one year for each scenario.

4.2 Input information

Any MFA or mass balance requires knowledge about the mass flows in the system (with the dimension of unit mass per units time). However, the information about the flows in a WWMS is usually given as volume flows or concentrations and not as mass flows. In this research, the information available in volume units was combined with the information about the density of the materials in order to carry out mass balances. The density used for the drinking water flows, for the rain flows and for the stormwater flows was 1 t m^{-3}. For the wastewater flows a density of 1 t m^{-3} $\pm$ 5% was used. For the sludge flows a density of 1.159 t m^{-3} $\pm$ 5% was used (based on Tchobanoglous et al. 2003).

The input information for the materials layer is presented in Table 4.2. Some of the mass flows were calculated from known parameters. Table 4.3 presents a list with the parameters used in the model and their corresponding values for each scenario. The equations used to calculate the input flows from the parameters are: Equation 4.1 for the flow Decentralized Water Supply, Equation 4.2 for the flow Rain, Equations 4.3 and 4.4 for the flows of N and P from the reservoir in the Households process and Equations 4.5 and 4.6 for the flow of N and P from the reservoir in the Decentral Sanitation process.

Where Wa_{Dec} is the water consumption per capita in decentral sanitation, Pop is the population number, A is the area of the city, P_{av} is the average yearly precipitation, PS is the percentage of population with access to public services of drinking water and sewerage, $Load_N$ is the N contribution to the wastewater per capita and $Load_P$ is the P contribution to the wastewater per capita. The conversion factor 365 was used to scale daily amounts to yearly amounts:

$$Decentralized\ Water\ Supply = Wa_{Dec} \cdot Pop \cdot (1 - PS) \cdot 365 \tag{4.1}$$

$$Rain = A \cdot P_{av} \tag{4.2}$$

$$N\ Load\ in\ Households = Load_N \cdot Pop \cdot PS \cdot 365 \tag{4.3}$$

$$P\ Load\ in\ Households = Load_P \cdot Pop \cdot PS \cdot 365 \tag{4.4}$$

$$N\ Load\ in\ Decentral\ Sanitation = Load_N \cdot Pop \cdot (1 - PS) \cdot 365 \tag{4.5}$$

$$P\ Load\ in\ Decentral\ Sanitation = Load_P \cdot Pop \cdot (1 - PS) \cdot 365 \tag{4.6}$$

Table 4.1 shows the calculated N and P input loads from Equations 4.3 to 4.6 used to model the processes Households and Decentral Sanitation. To calculate the remaining N and P flows in the substance layer of the model, it was required to use information about their concentrations in the flows. This information combined with the volumes used in the materials layer yields the total mass flow of each substance within the corresponding water flows. The concentrations for the substance layers are presented in Table 4.4. The calculation of the uncertainty for each input flow or concentration was done by analysing the probability distribution when possible or by expert consultation.

In many of the processes, the inflows of water or substances are not equally distributed amongst the number of outputs. Transfer Coefficients (TCs) were used in this case to describe the mass transfer of materials or substances from the inputs into the outputs. A transfer coefficient describes the partitioning of a material or a substance in a process. In other words, they describe how much of an input material or input substance is transferred to a specific output flow of the process. The TCs that were applied for the calculation of each scenario are shown and explained in Table 4.5.

Table 4.1: Calculated nitrogen and phosphorus inputs to homes (tonnes a^{-1})

Process	Nutrient	Scenario 2007	Scenario 2011	Scenario 2030
Households	N	1072 (± 50%)	1186 (± 50%)	1700 (± 50%)
	P	214 (± 40%)	237 (± 40%)	340 (± 40%)
Decentral Sanitation	N	56 (± 50%)	24 (± 50%)	35 (± 50%)
	P	11 (± 40%)	5 (± 40%)	7 (± 40%)

Source: Equations 4.3 to 4.6 and parameters from Table 4.3

Table 4.2: Initial input information for the scenarios: materials layer (1000 m^3 $year^{-1}$)

	Scenario			
Flow	**2007**	**2011**	**2030**	**Source**
Bottled Water	800 (± 20%)	856 (± 20%)	1,232 (± 20%)	Based on 1,2[a]
Decentralised Water Supply	734 (± 30%)	315 (± 30%)	451 (± 30%)	Equation 4.1
Groundwater	45,300 (± 10%)	57,000 (± 20%)	77,000 (± 20%)	Sc.2007: 3. Sc.2011 and 2030: based on 3,4[b]
Industrial Direct Discharge	3 (± 20%)	3 (± 50%)	5 (± 50%)	Based on 1,2[a]
Industrial Private Water Supply	3,400 (± 20%)	3,638 (± 20%)	5,236 (± 20%)	Based on 1,2[a]
NI/ND Direct Discharge	160 (± 20%)	171 (± 20%)	246 (± 20%)	Based on 1,2[a]
NI/ND Private Water Supply	4,600 (± 20%)	4,922 (± 20%)	7,084 (± 20%)	Based on 1,2[a]
Rain	54,899 (± 10%)	55,853 (± 10%)	67,000 (± 10%)	Equation 4.2
Wastewater to treatment plant El Punto	13,466 (± 10%)	23,652 (± 10%)	23,652 (± 10%)	3,4
Wastewater to treatment plant La Cantera	1,892 (± 10%)	1,892 (± 10%)	2,838 (± 10%)	3,4
Wastewater to treatment plant Forum	0 (± 0%)	3,154 (± 10%)	8,199 (± 10%)	4
Wastewater to treatment plant Delicias	0 (± 0%)	0 (± 0%)	3,154 (± 10%)	4

NI/ND=Non-Industrial/Non-Domestic
[a]The increase in the flows was considered as proportional to the population growth (7% from 2007 to 2011 and 54% from 2007 to 2030). [b]The water consumption patterns by 2030 were considered to remain similar as in 2007 and 2011.

1 - Public registry of water use (*Registro Público de Derechos del Agua*, REPDA), data base for year 2007 provided by CONAGUA Nayarit.
2 - CONAGUA 2012
3 - Castillo Delgado 2007
4 - Pers. comm. from SIAPA Tepic and CONAGUA Nayarit.

Table 4.3: Parameters used for the calculation of the input flows in the scenarios.

Code	Parameter and units	Scenario 2007	Scenario 2011	Scenario 2030	Source*
A	Area of the city (1000 m^2)	51,380 (± 10%)	55,876 (± 10%)	61,912 (± 10%)	1/2/Based on 1,2
P_{av}	Average yearly precipitation (m rain $year^{-1}$)	1.0685 (± 10%)	0.9996 (± 10	1.084 (± 10%)	3/4/5
Pop	Population (inhabitants)	309,291 (± 1%)	331,674 (± 3%)	475,411 (± 3%)	1,6,7
PS	Public services (%) of served population)	95 (± 0%)	98 (± 0%)	98 (± 0%)	8
Wa_{Dec}	Water consumption in decentral sanitation (m^3 inh^{-1} day^{-1})	0.130 (± 30%)	0.130 (± 30%)	0.130 (± 30%)	Based on 9
$Load_N$	N load in wastewater from households (g inh^{-1} day^{-1})	10.00 (± 50%)	10.00 (± 50%)	10.00 (± 50%)	Based on 10,11,12,13
$Load_P$	P load in wastewater from households (g inh^{-1} day^{-1})	2.00 (± 40%)	2.00 (± 40%)	2.00 (± 40%)	Based on 10,11,12,13

* Sources for each scenario are separated by /. Otherwise the same source was used for all scenarios.

1 - Castillo Delgado 2007
2 - INEGI 2011
3 - INEGI 2008
4 - INEGI 2012
5 - INEGI 2009 (historical average)
6 - H. XXXV Ayuntamiento de Tepic 2000
7 - Consejo Nacional de Población 2008
8 - Pers. comm. from SIAPA Tepic and CONAGUA Nayarit.
9 - CONAGUA 2010
10 - DWA 2008
11 - Martinez et al. 2011
12 - Tchobanoglous et al. 2003
13 - ArandaCirerol et al. 2011

Table 4.4: Initial input information for all scenarios: substance layers (mg L^{-1})

Flow and units	Nitrogen	Phosphorus	Source*
Groundwater	1.8 (± 26%)	0 (± 0%)	1 / 2
Industrial and NI/ND private water supply	1.8 (± 26%)	0 (± 0%)	1 / 2
Decentralised Water Supply	1.8 (± 26%)	0 (± 0%)	1 / 2
Drinking water flows	1.8 (± 26%)	0 (± 0%)	1 / 2
NI/ND Direct Discharge and NI/ND Wastewater	70 (± 20%)	16 (± 20%)	Based on 3
Industrial Direct Discharge and Industry Wastewater	30 (± 50%)	10 (± 50%)	Based on 4,5,6
Rain	0 (± 0%)	0 (± 0%)	2
Irrigation water	3 (± 50%)	0.6 (± 50%)	Based on 7, 8, 9
Stormwater Sewer Inflow and Stormwater Sewer Discharge	3 (± 50%)	0.6 (± 50%)	Based on 7, 8, 9
Bottled Water	0 (± 0%)	0 (± 0%)	2
Evaporation flows	0 (± 0%)	0 (± 0%)	2
Permanent Infiltration to Sewer	1.8 (± 26%)	0 (± 0%)	1 / 2
Infiltration from Soil to sewer (process City Area)	0 (± 0%)	0 (± 0%)	2
House roof inflow (process City Area)	3 (± 50%)	0.6 (± 50%)	Based on 7, 8, 9
Other inflows (process City Area)	14 (± 50%)	0.6 (± 50%)	Based on 7, 8, 9

NI/ND=Non-Industrial/Non-Domestic
*Sources for each nutrient separated by /, otherwise same sources were used.

1 – Data obtained from continuous water monitoring of SIAPA Tepic
2 – No information available: reasoned assumption
3 – Based on Tchobanoglous et al. 2003
4 – Single water analysis on site (Castillo Delgado 2007)
5 – Abwassertechnische Vereinigung ATV 2000
6 – Barnes et al. 1984
7 – Peters 2007
8 – Herrmann and Klaus 1997
9 – Martinez et al. 2011

Table 4.5: Initial input information: transfer coefficients

Process	Transfer coefficient: flow X → flow Y	2007	2011	2030	Source*
Water Supply	Groundwater → Industrial Use	0.003	0.002	0.003	1
	Groundwater → NI/ND Use	0.150	0.130	0.140	1
	Groundwater → Water Losses	0.230	0.350	0.300	2,3,4
	Water losses → Permanent Infiltration.	0.200	0.200	0.200	4
Households and NI Use	Σ Inputs → Water Lost	0.250	0.250	0.250	5
Wastewater Sewer	Σ Inputs → Wastewater Exfiltration	0.150	0.150	0.150	4,6
	Σ Inputs → WW Sewer Export	0.200	0.070	0.030	4
City Area	Rain → Rain to Sealed Areas	0.700	0.700	0.700	4,7
	Rain to Sealed Areas → Evaporation (1)	0.050	0.050	0.050	4
	Rain to Sealed Areas → Runoff to Soil	0.030	0.030	0.030	4
	Rain to Sealed Areas → House Roof Inflow	0.125	0.125	0.100	4,8
	Rain to Sealed Areas → Other Inflows	0.100	0.050	0.030	4
	Rain to Unsealed Areas → Evaporation (2)	0.300	0.300	0.300	4
	Rain to Unsealed Areas → Infiltration from Soil	0.100	0.100	0.100	4
Stormwater Sewer	S-Sewer Inflow → Irrigation Water	0.100	0.100	0.100	9
	S-Sewer Inflow → S-Sewer Discharge	0.800	0.800	0.800	4
WWTP	WW to [name of WWTP] → Discharge [name of WWTP] (all scenarios)		0.999		Based on 10,11,12
	Σ $Input_{Nitrogen/Phosphorus}$ → Discharge Cantera (all scenarios)		0.67 / 0.74		Based on 13,14
	Σ $Input_{Nitrogen/Phosphorus}$ → Sludge Cantera (all scenarios)		0.15 / 0.26		Based on 13,14
	Σ $Input_{Nitrogen}$ → Discharge Punto	0.95	0.65	0.65	Based on 12/14,15,16
	Σ $Input_{Phosphorus}$ → Discharge Punto	0.95	0.60	0.60	Based on 12/14,15,16
	Σ $Input_{Nitrogen/Phosphorus}$ → Discharge Delicias and Discharge Forum (all scenarios)		0.65 / 0.60		Based on 14,15,16

NI/ND: Non-Industrial/Non-Domestic, S-Sewer: Stormwater Sewer, WWTP: Wastewater Treatment Plants.
*Sources for each scenario separated by /, otherwise same sources were used.

1 – Calculations based on user registry from SIAPA Tepic
2 – Castillo Delgado 2007
3 – Pers.comm. with SIAPA Tepic
4 – Assumption under expert consultation
5 – CONAGUA 2010
6 – Martinez et al. 2011
7 – Approximation to sealing degree of the city based on satellite images.
8 – Approximate calculation of house roofs and paved yards areas in the city (details in Annex A).
9 – Peña Fernández 2008
10 – Herrmann and Klaus 1997
11 – Huang et al. 2007
12 – Tchobanoglous et al. 2003
13 – Kroiss and Zessner 2001
14 – Zessner and Lindtner 2005
15 – Sperling 1996
16 – Lauver and Baker 2000

4.3 Results and discussion

This chapter summarizes the results of the simulations carried out for scenarios 2007, 2011 and 2030. At first, an overview of inputs and outputs to the system is presented followed by the results obtained of selected relevant indicators. The complete results of the MFA for all flows and layers of scenarios 2007, 2011 and 2030 as obtained in STAN are included in Annex A. The discussion focuses on the comparison of the situation in the different scenarios and not on the absolute values. Following aspects are discussed:

- Water and nutrient sources
- Water and nutrient disposal routes
- Water use (consumption and pollution)
- Sewer performance.

The MFA was carried out in an iterative simultaneous manner for all layers in order to balance out the whole system under consideration of the uncertainties in both materials and substance flows. Initial mass flows and initial concentrations are used to start the calculations and in order to calculate the unknown flows. Due to the uncertainties in the input values, it is possible that the calculated flows and concentrations differ from the initial input values after the data reconciliation. In all cases the calculated flows remain within the uncertainty limits of the input data.

4.3.1 Sources and disposal routes

Water

To analyse the water balance in the city, the sources (called imports) and disposal routes (called exports) displayed in Figure 4.1 were grouped according to their characteristics. The groups are:

- Sources
  - Groundwater imports.
  - Rain imports.
- Disposal routes
  - Clean water exports (drinking water or non-polluted stormwater infiltrating into the soil or evaporating).
  - Dissipated water (at housedholds and NI Use. In the model expressed as a sink).

- Exports from the WWTPs (discharge and sludge).
- Exports from the Stormwater Sewer (Polluted Stormwater).
- Exports of raw sewage to the environment (from the WW Sewer and from the users directly).

A balance of the water imports and exports of all scenarios is presented in Figure 4.8. The results indicate that groundwater and rain contribute equally to the total imports in the scenario 2007. Both imports increase constantly in the scenarios, except in scenario 2030-Dry, where the imports are at its lowest due to the assumed drought conditions.

The increase in groundwater imports can be explained by the population growth: the increased number of inhabitants requires in total more groundwater to cover its needs. The rain imports depend on the annual precipitation and on the city area. The annual precipitation in all the basic scenarios (2007, 2011, 2030) is very similar, about 1 m rain a^{-1}. However, the city area (the catchment area) increases largely between 2011 and 2030 and this generates a net increase of the rain imports by 2030. Nevertheless, the rain imports increase more slowly than the groundwater imports; in scenario 2007, 50% of the total imports are due to rain. In scenario 2011, this percentage decreases to 46% and in scenario 2030 to 43%. In the scenario 2030-Dry the share of rain amounts to 27% whereas in the 2030-Rainy scenario rain import represents 53%. These results point out an a increasing dependence on the aquifer as the inhabitants number in the city increases. The share of Rain in the total imports may be interpreted as an indirect indicator of potential groundwater recharge. As this share decreases, the city may be approaching overexploitation of its aquifer.

The largest exports in scenario 2007 are those of the stormwater sewer (33%) followed by the exports of clean water (24%). The exports of raw sewage amount to 20% in the same scenario and the exports of the WWTPs amount to 14%.

These ratios change in the later scenarios but not in a drastic way. The stormwater sewer exports decrease to 27% in scenario 2011 and, in scenario 2030, they are 25% of the total exports. The most significant changes are observed in the share of WWTP exports which increases to 24% in 2011 and stay constant in 2030. The exports of raw sewage to the environment decrease from 20% in scenario 2007 to 13% and 15% in scenarios 2011 and 2030 respectively.

The differences between scenarios 2030 and 2030-Dry with respect to export flows are explained by a decrease of the total stormwater sewer exports as well as a decrease of the total raw sewage exports. In the 2030-Rainy scenario the opposite is observed: the exports of the stormwater sewer increase as well as the total exports of raw sewage. This is due to the increase in the rain imports which do not only affect the Stormwater Sewer but also the WW Sewer.

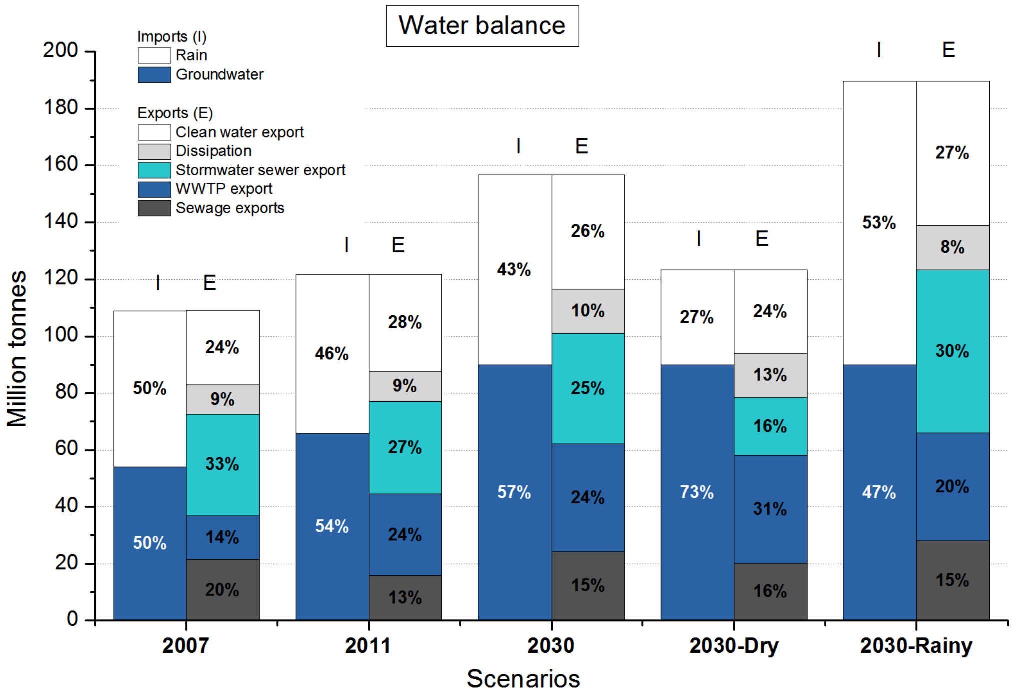

Figure 4.8: Water sources and disposal routes in the basic scenarios

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Nitrogen and phosphorus

The emission of nutrients to the environment is a criterion that is conventionally used to assess the efficiency of wastewater systems (Meinzinger 2010). To compare the balance of nutrients with the balance of water, a summary of the import and export routes was made using the same groups as in the water balances. However, in the balance of nutrients two further categories are relevant and were included: the import of nutrients from food and chemicals supplies and the export of nitrogen through denitrification. Figure 4.9 and Figure 4.10 show the nitrogen and phosphorus balances for all scenarios.

The main import route of the nutrients in all scenarios is through the food and chemicals supplies (88–92% of total imports). The import of nutrients from groundwater sources and from the sealed areas is less significant.

The main nutrient export route in 2007 is the sewage export followed by the exports through the WWTPs. In all other scenarios the main export route is via the WWTPs followed by the sewage exports. This shift is achieved due to the construction and operation of the additional WWTPs in the later scenarios. The wastewater is then directed to the treatment facilities instead of being directly discharged to the river.

A significant decrease is observed in the nutrient exports through the stormwater sewer from 22% in 2007, to 11% in 2011 and 6% in 2030. This is due to the continuous reduction of the interconnections between the WW Sewer and the stormwater sewer so that less nutrients leave the system via this route.

The export of nitrogen through denitrification routes is 1% or less in all scenarios. The construction or extension of the wastewater treatment facilities did not have an influence in the elimination of N and P or their recovery from the wastewater because the installed technologies focus on the reduction of the organic load and are not designed to enhance denitrification or for P removal. Nevertheless, positive changes in the nitrogen chemical form are expected due to the treatment such as the conversion of ammonia to nitrate. Ammonia in untreated flows is toxic towards fish at alkaline pH and is oxygen-depleting. Treated N forms are not oxygen-depleting. However, they can still cause eutrophication of water bodies (Schwedt 2001).

The emissions of nutrients can be alternatively classified according to their destination in the environment, which can be soil/groundwater or surface water. In the case of nitrogen, a third export destination is the atmosphere due to transformation of N compounds to gaseous nitrogen by denitrification at the WWTPs.

Figure 4.11 shows a summary for the exports of nitrogen and phosphorus according to their destination for all scenarios. The exports going to the soil/groundwater are: irrigation water from the stormwater sewer, wastewater exfiltration from the WW Sewer, groundwater recharge, and the sludge flows from the WWTPs. The export flows going to the surface water are: direct wastewater discharges of all users, direct discharges of the stormwater sewer, direct discharges of the WW Sewer and discharge of treated wastewater from the WWTPs.

From all scenarios it can be concluded that the main destination of both nutrients are the surface waters. However, a reduction of the exports to the surface water is achieved between years 2007 and 2011. While in 2007 82%/83% of the total N and P exports were discharged to the surface water, by 2011 this is reduced to 65%/63% and is kept constant in the later scenarios. This reduction is achieved by the construction and operation of the additional WWTPs which concentrate the nutrients in the sludge generated by the treatment and which is finally disposed of on top of empty fields or at the local waste dump.

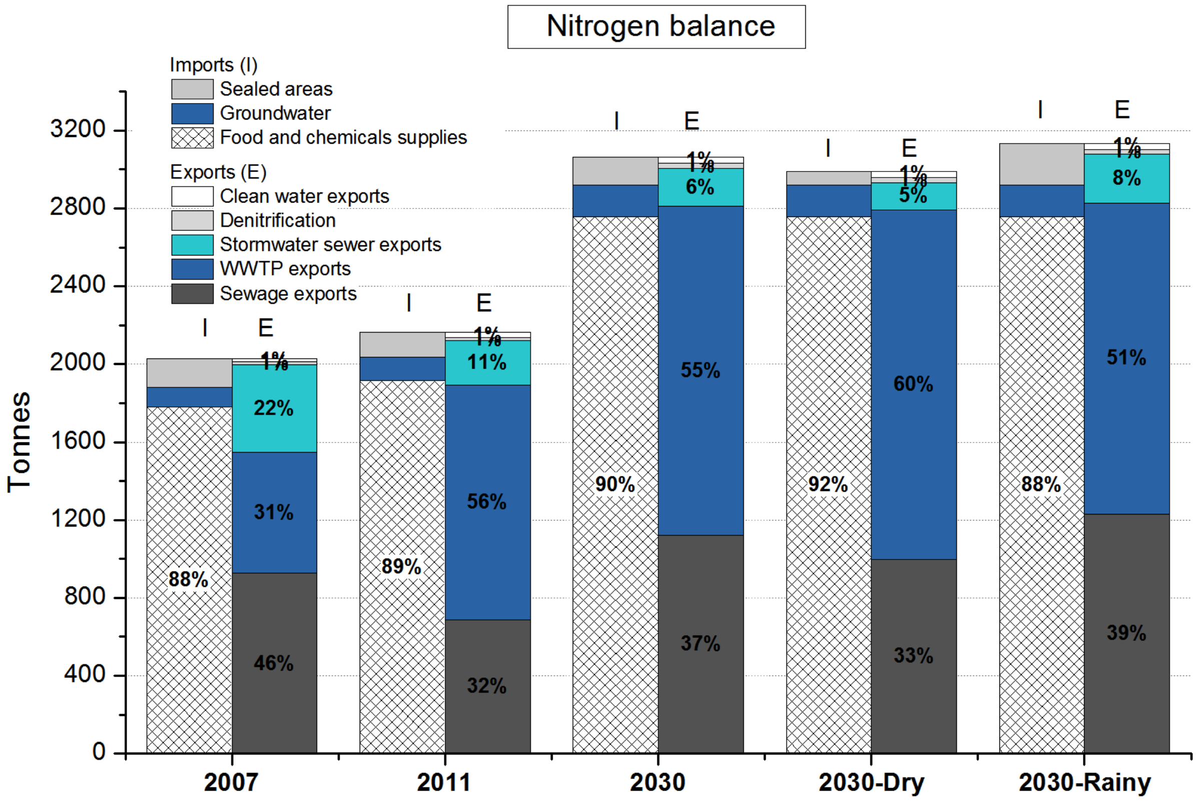

Figure 4.9: Nitrogen sources and disposal routes in the basic scenarios

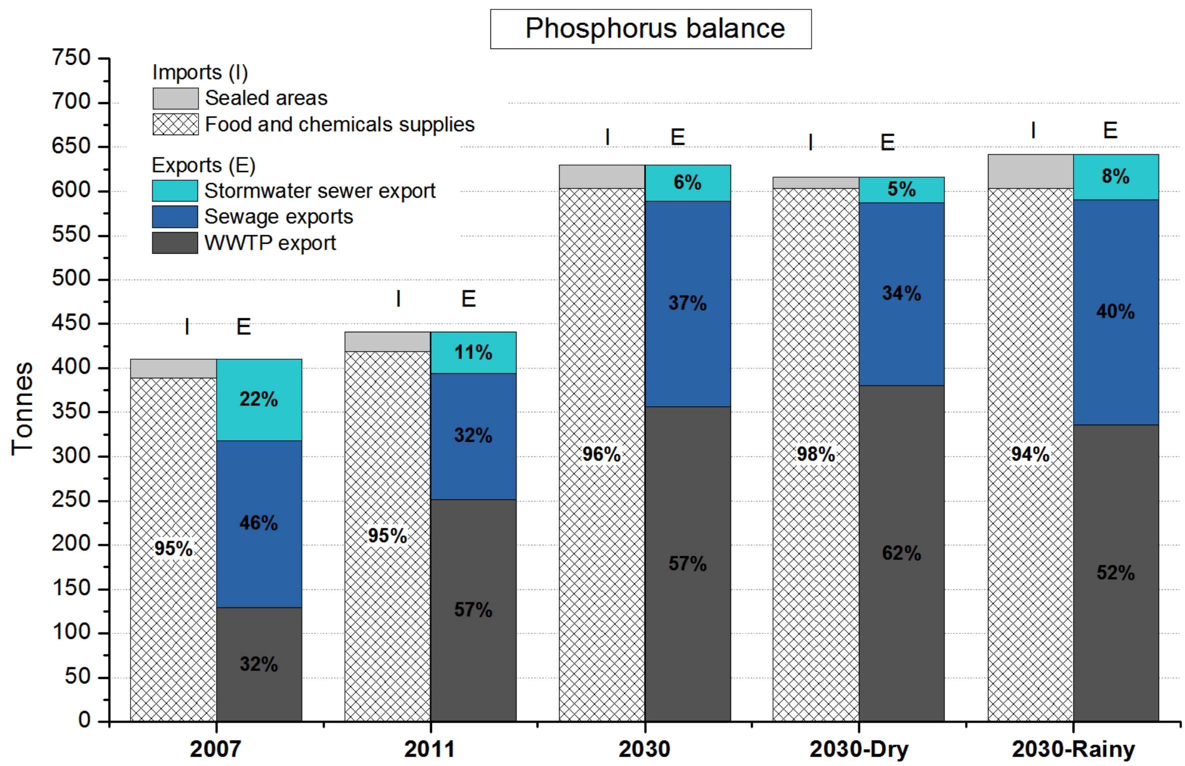

Figure 4.10: Phosphorus sources and disposal routes in the basic scenarios

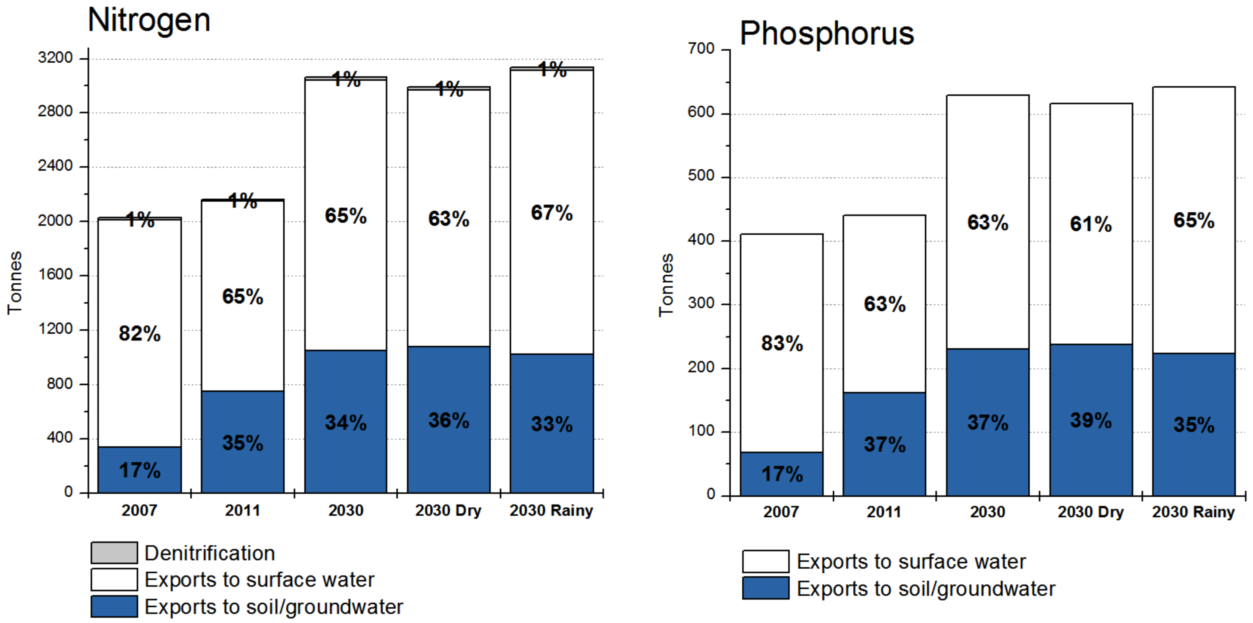

Figure 4.11: Nutrient exports according to their destination in the environment. (percentages refer to annual total)

4.3.2 Water consumption and wastewater generation

With the results of the MFA it was possible to identify the current trends for water consumption and pollution in the city with a holistic approach. It was found that Households in Tepic are the major water consumers as well as the major wastewater producers in all scenarios. They obtain water from public sources and discharge exclusively to the public WW Sewer. Decentral Sanitation plays a marginal role in the water consumption and wastewater generation given the high coverage degree of the public services in the city.

The NI/ND Use uses a balanced mix of water from both public and private sources and the Industry obtains water almost exclusively from private sources. The main discharge route of both users is the WW Sewer.

Figure 4.12 summarizes the water supply and wastewater destination trends in the city as modelled within scenario 2011. The trends in the city in scenario 2007 were very similar. The trends for scenario 2030 are a projection of the trends observed in scenarios 2007 and 2011.

4.3.3 Per capita water consumption at households

In Tepic, water consumption measurement takes place at less than 5% of the users (H. XXXVIII. Ayuntamiento de Tepic 2009). For this reason the calculation of the average water consumption per capita in Households was performed based on the number of inhabitants and on the information provided by the SIAPA regarding yearly water abstraction volumes, water losses and service coverage.

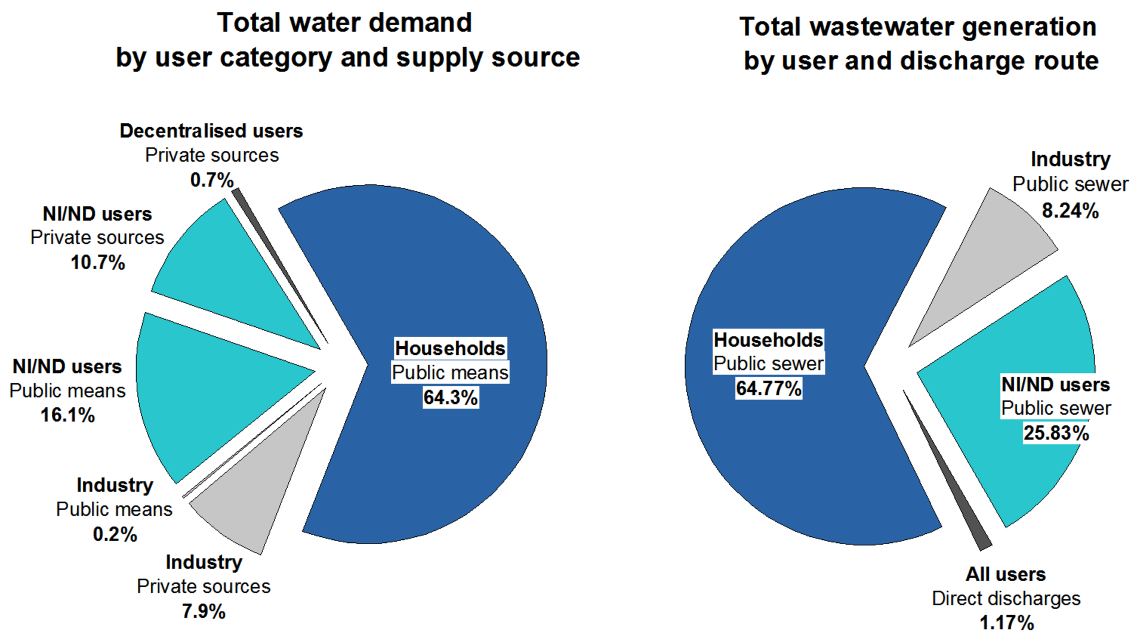

Figure 4.12: Trends in water supply and wastewater discharge in scenario 2011.
NI/ND = Non-Industrial/Non-Domestic

The calculated domestic average water consumption in scenario 2007 was 0.264 m^3 inh^{-1} day^{-1} and for scenario 2011 it was 0.249 m^3 inh^{-1} day^{-1}.

The slight decrease in the figures for the year 2011 cannot be considered with certainty as a decrease of the per capita water consumption since the calculation includes the volume measurement errors as well as inaccuracies in the total population number for those years.

According to the Mexican planning guidelines (CONAGUA 2007), the water consumption of wealthy people in a city like Tepic is 0.300 m^3 inh^{-1} day^{-1} while the middle class consumes 0.200 m^3 inh^{-1} day^{-1} and people with low socioeconomic level consume 0.130 m^3 inh^{-1} day^{-1}.

The water users are supposed to pay fees according to their classification in the users registry of the SIAPA. The reviewed registry indicates nearly 90% of the users in the category of "low socioeconomic level". Based on the guideline values, the average daily per capita water consumption in Tepic would be thus expected to be close to 0.130 m^3, but the water consumption per capita calculated in this study is almost twice as much. This observation indicates a misfit between the user classification and the actual consumption.

4.3.4 Sewer performance

The performance of the public sewer system was evaluated based on the results of the water layers of the model. Four indicators are used to compare the performance of the system in scenario 2007 against all other scenarios. The chosen indicators are: infiltration, wastewater sewer exports, direct wastewater discharges and treatment coverage of the wastewater (referred to secondary treatment of wastewater). The indicators relate the relevant flows to appropriate scaling factors in order to assess the changes in the scenarios under consideration of the population growth and of the city expansion.

Infiltration

The total infiltration to the sewer Q_{inf} is obtained by adding the flows Permanent Infiltration and Seasonal Infiltration. This is compared to the wastewater inputs to the sewer Q_{ww} (which are composed of flows NI/ND Wastewater, Households Wastewater and Industry Wastewater) to calculate the Additions by Infiltration (AI) as shown in Equation 4.7. This calculation is equivalent to the German infiltration indicator called *Fremdwasserzuschlag*.

$$Additions\ by\ Infiltration\ (AI) = \frac{Q_{inf}}{Q_{ww}} \cdot 100\% \tag{4.7}$$

Table 4.6 shows the results of the simulations for the flows Seasonal Infiltration and Permanent Infiltration as well as the wastewater inputs to the sewer. The infiltration rate is shown in the last column. An increase in Permanent Infiltration is observed as well as a decrease in Seasonal Infiltration. Overall, a positive reduction of the infiltration from 2007 to 2030 can be expected: in 2007, an infiltration equivalent to 38% of the wastewater flows entered the sewer. In 2011 the infiltration was equivalent to 36% and in 2030 it will be 25%. The Sub-scenario 2030-Dry had the lowest Seasonal Infiltration with 17% whereas 2030-Rainy indicated a higher one with 34%.

The Permanent Infiltration flow depends on the Water Losses flow from the Water Supply process. There was a constant increase in the Groundwater input to the Water Supply process and in the water losses coefficient. Thus, the Permanent Infiltration increased from scenario 2007 to scenario 2011 and a further increase is predicted in scenario 2030.

In contrast, the Seasonal Infiltration decreased gradually. This flow directly depends on the rain imports which are related to precipitation and catchment area. The precipitation values for the three basic scenarios were very similar, but the catchment area (city area) increased from scenario to scenario. An increase in Seasonal Infiltration could have been expected as a result. However, the TCs for the stormwater infiltrating the WW Sewer decreased in the scenarios. This decrease in the TCs is explained by the improvements in the WWMS of Tepic consisting of maintenance of manholes and slabs and reduction of the direct connections of house roofs and paved house yards to the WW Sewer (improvement measures described in Table 3.2, TCs for all scenarios shown in Table 4.5). In addition, the flow Q_{ww} (wastewater generation) increased at a larger rate than the catchment area did. All these factors together explain the decrease in the AI.

In the dry scenario the AI is much lower simply because there are less Rain imports. In turn, in the rainy scenario the AI has a higher value as a result of the much larger precipitation.

Table 4.6: Infiltration in the basic scenarios (flows in 10^6 tonnes a^{-1})

Scenario	Seasonal Infiltration	Permanent Infiltration	Wastewater to sewer Q_{ww}	Additions by Infiltration
Scenario 2007	10.41 (± 1.04)	2.08 (± 0.21)	32.70 (± 3.64)	38%
Scenario 2011	8.64 (± 0.86)	3.99 (± 0.79)	34.77 (± 6.46)	36%
Scenario 2030	8.25 (± 0.82)	4.62 (± 0.92)	50.48 (± 9.36)	25%
Scenario 2030-Dry	4.13 (± 0.41)	4.62 (± 0.92)	50.48 (± 9.35)	17%
Scenario 2030-Rainy	12.31 (± 1.23)	4.62 (± 0.92)	50.48 (± 9.37)	34%

Sewer export and exfiltration

The Sewer Export and the Wastewater Exfiltration are known parameters and they were specified in the input informations for the MFA (as transfer coefficients, Table 4.5). The calculated flows in each scenario are shown in Table 4.7.

Table 4.7: Sewer Export and Wastewater Exfiltration in the basic scenarios (10^6 tonnes a^{-1})

Scenario	Sewer Export	Wastewater Exfiltration
Scenario 2007	9.04 (± 0.63)	6.78 (± 0.47)
Scenario 2011	3.32 (± 0.45)	7.11 (± 0.97)
Scenario 2030	1.90 (± 0.27)	9.50 (± 1.36)
Scenario 2030-Dry	1.78 (± 0.27)	8.88 (± 1.36)
Scenario 2030-Rainy	2.02 (± 0.27)	10.11 (± 1.37)

The overall decrease of the Sewer Export flow is explained by the reduction of the TC defining this flow. The TC was reduced from one scenario to the next in order to reflect the elimination of interconnections between the WW Sewer and the Stormwater Sewer and the reduction of the illegal discharges of wastewater to the Stormwater Sewer.

Since no significant improvements of the pipeline network were carried out or are planned (Table 3.2), the TC defining the exfiltration rate remained unchanged for all scenarios leading to a constant increase of the exfiltrated volumes as the total input to the WW Sewer increases. This flow remains a constant threat for the aquifer.

Secondary treatment coverage

To calculate the secondary treatment coverage, the sewer inputs are compared to the installed secondary treatment capacity. Two different approaches for calculating the sewer inputs were followed:

1. The first approach for calculating the secondary treatment coverage considers only the theoretical sewer inputs in the calculations. The theoretical sewer inputs are equal to the wastewater inputs generated by the users in the city. This approach can be considered as the conventional way of calculating the treatment coverage.

2. The second and more integral approach for calculating the secondary treatment coverage includes in the calculations not only the wastewater inputs, but also the infiltrations to the sewer. The infiltrations to the sewer are originated by the interactions of the WW Sewer with the processes Water Supply, Stormwater Sewer and City Area and lead to a net increment of the sewer inputs.

Table 4.8 shows a summary of the installed secondary treatment capacity, the wastewater generation and the infiltrations to the sewer for each scenario as well as the coverage calculated under the first approach (Coverage (1)) and the second approach (Coverage (2)).

Table 4.8: Secondary treatment coverage in the basic scenarios (flows in 10^6 tonnes a^{-1})

Scenario	Secondary treatment capacity	Wastewater inputs to sewer	Infiltrations to sewer	Coverage (1)	Coverage (2)
Sc. 2007	1.89 (± 0.13)	32.70 (± 3.64)	12.50 (± 1.25)	6%	4%
Sc. 2011	28.72 (± 3.21)	34.78 (± 6.46)	12.63 (± 1.65)	83%	61%
Sc. 2030	37.87 (± 4.23)	50.48 (± 9.36)	12.87 (± 1.74)	75%	60%
Sc.2030-Dry	37.87 (± 4.23)	50.48 (± 9.35)	8.75 (± 1.33)	75%	64%
Sc.2030-Rainy	37.87 (± 4.23)	50.48 (± 9.37)	16.93 (± 2.14)	75%	56%

Coverage (1) is based on the comparison of treatment capacity to wastewater inputs to the sewer.
Coverage (2) is based on the comparison of treatment capacity to wastewater inputs to the sewer and infiltrations into the sewer.

A large increase in the secondary treatment coverage is observed from 2007 to 2011 (from 6% to 83% under the conventional approach and from 4% to 61% under the integral approach). In the conventional approach, the treatment coverage decreases from 82% in 2011 to 75% in 2030 while in the scenarios 2030-Dry and 2030-Rainy the treatment coverage is the same as in scenario 2030.

In the integral approach (Coverage (2)), the treatment coverage in the scenarios 2011 and 2030 is very similar (61% and 60%), but it differs in the subscenarios for

2030: the coverage increases to 64% in the 2030-Dry scenario, while it decreases to 56% in the 2030-Rainy scenario.

The large improvements between 2007 and 2011 are mainly achieved by the expansion of the secondary wastewater treatment capacity: while in 2007 only 1.89 10^6 m^3 $year^{-1}$ of wastewater received secondary treatment, in 2011 the figure rose to 28.72 10^6 m^3 $year^{-1}$. In scenario 2030 the capacity raises again to 37.87 10^6 m^3 $year^{-1}$. Despite of the constant increase of the secondary treatment capacity, the indicator does not show a further increase in scenario 2030 under any of the approaches because the increase in the wastewater inputs exceeded the increase of the treatment capacity. The infiltrations to the sewer are directly related to the precipitation. This explains the differences in the performance among the scenarios for 2030 under the integral approach.

The integral approach provides always a lower result than the conventional approach given that a larger input to the sewer is considered in the calculations. It is assumed that the integral calculation is closer to reality. Since it includes the influence of the rain precipitating over the system as well as the interactions between the different components of the WWMS in the city, it reflects real operating conditions in a better way than the conventional approach.

4.3.5 Nutrients in the export flows

The Mexican wastewater guidelines for the reuse of water in agriculture are 40 mg/L for N and 20 mg/L for P as monthly average (SEMARNAT 1997). The calculated N and P concentrations in the discharge of all WWTPs are below those limits in all scenarios. The N concentrations at the Direct Discharge from the WW Sewer, at the NI/ND Direct Discharge and at the Decentral WW emissions exceed the mentioned limits in all scenarios. The maximum allowed P concentration is only exceeded in the Decentral WW emissions in all scenarios.

For the protection of aquatic life, the Mexican guidelines are lower: 15 mg/L for N and 5 mg/L for P. These limits were exceeded in all scenarios at all direct wastewater discharges from the WW Sewer, from the users and from Decentral Sanitation, in discharges of all WWTPs and in Polluted Stormwater Sewer Outflow.

4.4 Plausibility analysis

To test the plausibility of the MFA results for the modelled water consumption, the calculated per capita water consumption at households was compared against the results of a water measurement campaign at 30 homes in Tepic carried out on behalf of the CONAGUA Nayarit in 2007. The results of the measurement campaing are displayed in figure 4.13 together with the results of the water consumption calculations in this research. The consumption calculated in this study was within one standard deviation of the average consumption measured in the reference study and thus, the results for this first criterion were confirmed.

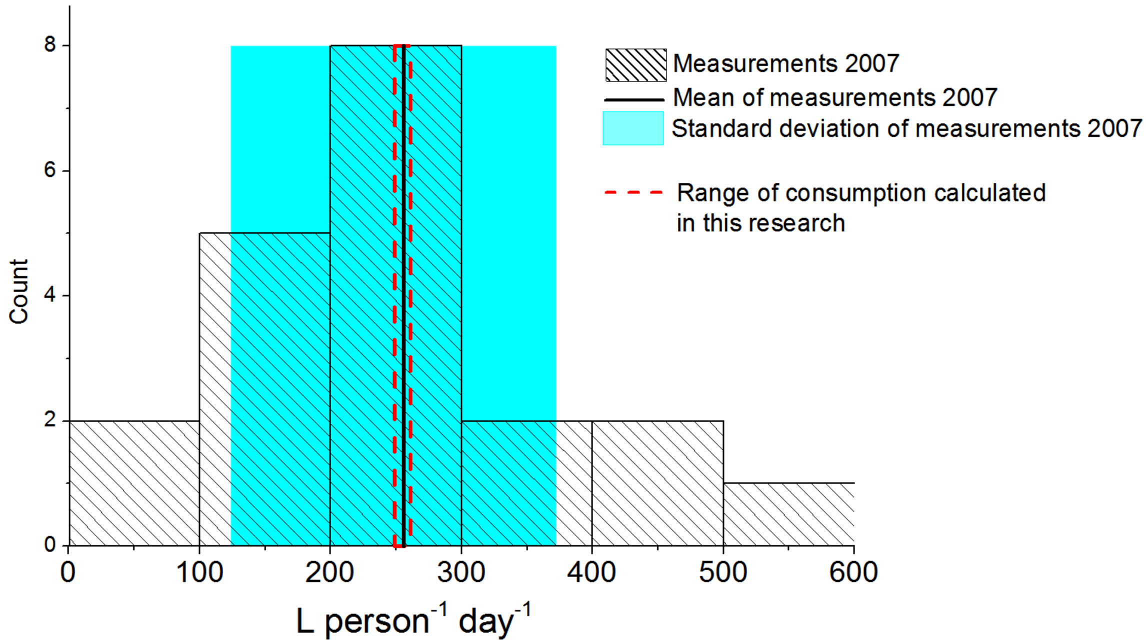

Figure 4.13: Water consumption measurements from Castillo Delgado 2007 vs calculated consumption from this research

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For a second plausibility test, selected N and P concentrations obtained in scenario 2011 were compared to reference values (Table 4.9 and Figure 4.14). The comparison indicates that the simulated values for the nutrient concentrations at the Households Wastewater are in a plausible range. However, the values obtained in the simulations for the sewer outflows are higher than the values obtained from samplings at the location. This is especially critical for the N concentrations, the simulated values of which hardly overlap with the reference values.

Since this critical criterion was not met to a satisfactory extent, no more plausibility criteria were applied to the results. It was decided to analyse the potential explanations for the differences and to evaluate the usefulness of the basic scenarios as far as possible before continuing with a second iterative step to improve the MFA.

Table 4.9: Nutrient concentrations in selected flows of scenario 2011 (mg/L)

Flow		Nitrogen	Phosphorus	Source
Household wastewater				
	from scenario 2011	54.4 (± 49%)	10.4 (± 43%)	-
	from literature	70.0	16.0	1
	from literature	40.6	6.95	2
Exfiltration				
	from scenario 2011	42.40 (± 30%)	8.60 (± 25%)	-
	from sampling in Tepic	20.5 (± 31%)	7.70 (± 56%)	3
Influents of Wastewater treatment plants (WWTP)				
	from scenario 2011	42.40 (± 30%)	8.60 (± 25%)	-
	Measurement at entrance of WWTP Cantera (WWTP with smallest catchment area)	32.60	5.30	4
	Design parameter at WWTP Forum (WWTP with second largest catchment area)	23.33 (± 50%)	5.62 (± 22%)	5
	Design parameter at WWTP El Punto (WWTP with largest catchment area)	18.64 (± 54%)	7.31 (± 29%)	6

1-Typical concentrations in undiluted domestic wastewater by consumption of 240 L inh^{-1} day^{-1}(Tchobanoglous et al. 2003)
2-Measured concentrations at households of a Mexican city with a per capita water consumption of 154 L inh^{-1} day^{-1} (Martinez et al. 2011)
3-Sampling in sewer pipelines of residential areas during rainy season (Espinosa Gutiérrez et al. 2015)
4-Single water analysis in dry season by a private laboratory (Castillo Delgado 2007)
5-Design documents, sampling in dry season(CONAGUA 2008c)
6-Design documents, sampling in dry season (CONAGUA 2008a)

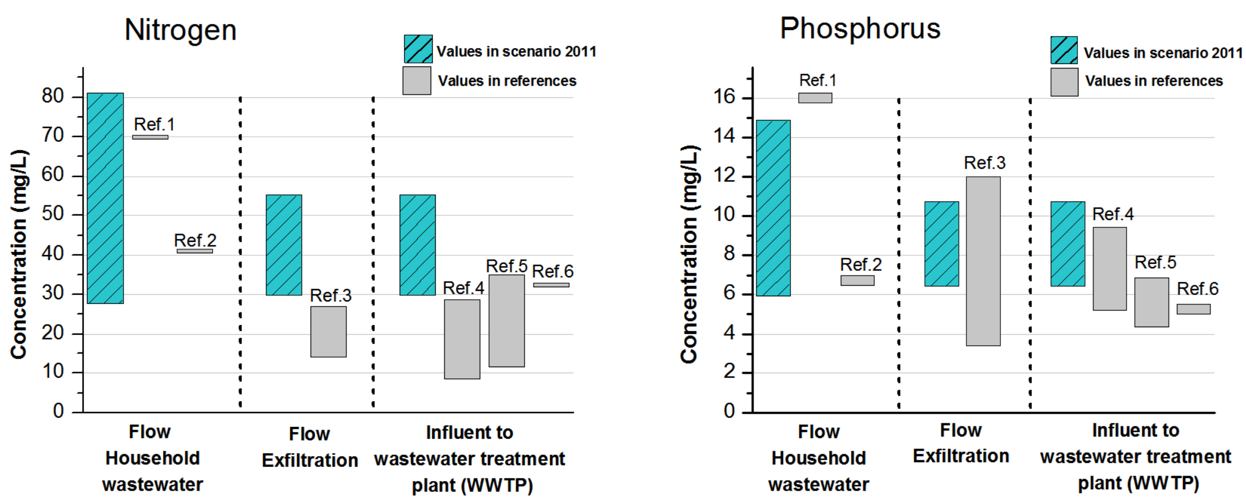

Figure 4.14: Nutrient concentrations in selected flows of scenario 2011.
Reference values: Ref.1-Tchobanoglous et al. 2003, Ref.2-Martinez et al. 2011, Ref.3-Espinosa Gutiérrez et al. 2015, Ref.4-Castillo Delgado 2007, Ref.5-CONAGUA 2008c, Ref.6- CONAGUA 2008a.

4.4.1 Error sources

The differences in the nutrient concentrations were expected to a certain extent. The simulations were carried out under static and perfect mixing conditions in a yearly scale, while the reference values reflect the nutrient concentrations in flows at specific locations, at certain moments or periods of the year and do not necessarily correspond to perfect mixing conditions. However, the reference values originate from water analysis obtained in both dry and rainy seasons in different years and from different locations. Nevertheless, they are always lower than the calculated ones on average. This tendency is more clearly observable for N concentrations. This is contradictory because the calculated N values are considered to be more reliable than the P values in as much as more data was available for the N simulations.

After evaluating the results and the input informations, a clear trend for a higher nutrient dilution in the sewer under real operating conditions was recognized. After discussing with local experts, the following reasons were found to explain this trend:

1. The actual water input to the system from private sources (Industry, NI/ND Use) might be larger than stated in the public registry of water use.
2. There could be additional water imports or infiltrations to the system which were not included in the simulations. For example, surface runoff from nearby mountains or a high groundwater table during the whole year.
3. The TCs describing the Seasonal Infiltration (process City Area) and the Permanent Infiltration (process Water Supply) might be higher in reality than the values obtained from expert consultation.
4. The measured reference values might be erroneous.
5. The nutrient input flows, which were based on literature values and used in the scenarios, might be higher than the actual ones.

Explanations 1-3 are considered the most likely. This would impact the calculated scenarios through a larger volume of inputs to the WW Sewer and a dilution of the nutrient concentrations in its outflows. This would also reduce the overall treatment coverage .

Explanation 4 is also a possibility. However, it is not possible to track this potential explanation for the observed concentration differences. The probability that all samplings and previous analyses are erroneous is considered as very low.

Explanation 5 is also not considered very likely, since this would mean an undernourished population, less polluting industrial processes and very clean sealed surfaces in the city. According to the observations made on site during this study, this is not the case. Besides, the major contribution of nutrients to the municipal wastewater is through the Households and the values obtained in the simulations for the wastewater originated from this process were in a plausible range.

In conclusion, the main explanation for the lower concentrations of nutrients at the outflows of WW Sewer is that the actual total volume of water entering the sewer might be larger than estimated by the operating company of the WWMS and larger than considered by the basic scenarios.

As the reference values in Table 4.9 show, the N concentration at the entrance to the WWTPs decreases as the catchment area increases. If catchment area is considered as an indicator of pipeline length and of infiltration risk (the larger the catchment area, the larger the infiltration risk), this observation clearly indicates the existence of infiltrations to the sewer system of the city.

The fact that the dilution is more marked in the N concentration than in the P concentration can be explained by an extensive use of P containing chemicals in the city (e.g. for cleaning purposes) or by a higher concentration of P in the groundwater and drinking water. However, there was no sufficient data about the P content in the imports of the city to further analyse this possibility.

4.5 Conclusion of basic scenarios

The basic scenarios met the tested plausibility criteria for the water consumption and for the wastewater generation. However, the plausibility criteria for the flows downstream of the WW Sewer were not met. This does not mean the failure of the MFA. Brunner and Rechberger (2004) and Montangero (2007) recognize that a first rough MFA is the first necessary step in a series of iterative approaches towards a complete MFA (see Figure 1.4) and it is also a useful basis to detect missing information in the system.

The basic scenarios are the first integral representation of the water metabolism in Tepic. They are useful to describe the current trends for water use and wastewater generation in the city. They are also useful to compare the situation of the WWMS before and after improvement measures implemented in the city between 2007 and 2011 and can be used as basis for a first projection of the future situation of the WWMS considering the planned improvements.

Similar to the work carried out by Kenway et al. (2011) at several Australian cities, this first evaluation of Tepic can be considered as a "snapshot" of the city in each of the selected years. The first snapshot for 2007 creates a baseline against which future changes can be assessed. In other words, by comparing the later snapshots to the 2007 baseline it is possible to observe the impacts of city management measures on the WWMS.

The conclusions for the basic scenarios for the flows upstream and downstream the WW Sewer are discussed separately below.

4.5.1 Water use and wastewater generation

In the basic scenarios, the imports of groundwater and rainwater to the city have almost the same magnitude. Nevertheless, the city relies solely on groundwater sources for its activities and rain harvesting is not purposed. Furthermore, the supply of water through the public mains prevails amongst the users (except for the industrial users, who obtain their water mainly from private sources). The domestic users (process Households) are the most important water consumers and also the most important wastewater generators in terms of volume followed by the NI Users. The main discharge route for the generated wastewater is the public sewer: more than 98% of all generated wastewater is conducted to the WW Sewer.

The largest nutrient imports to the WWMS are through food and chemicals supplies. The import of nutrients through other routes such as Groundwater flows and nutrient inputs from Sealed Areas represents together 8-12% of the total import in all scenarios.

With respect to water consumption at homes, it was found that the average water consumption per capita is larger than considered by the planning guidelines. The calculated average consumption in scenarios 2007 and 2011 was 0.261 m^3 inh^{-1} day^{-1} and 0.249 m^3 inh^{-1} day^{-1}, respectively. From the domestic contracts in the public water supply registry, 90% are in the category of "low socioeconomic level" and the Mexican guidelines indicate an average consumption of 0.130 m^3 inh^{-1} day^{-1} for households in this category. Thus, the calculated average consumption is almost twofold than the consumption mentioned by the guideline. If the users pay fees based on a mistaken assumption of low consumption, the water fees might not cover for the actual water supply costs.

4.5.2 Sewer balance and performance

Although the plausibility criteria for the sewer outflows were not met, it is considered that the results of the simulations represent the actual trends and that general conclusions can be drawn regarding the balance of inputs and outputs to the sewer as well as regarding its performance.

The observed trend indicates improvements in the performance of the sewer compared to the situation in 2007. However, several negative conditions prevail in all scenarios. The water infiltrations to the WW Sewer in Tepic remain as a constant problem in all considered scenarios despite of having a separated sewer system and implementing improvement measures to both stormwater sewer and wastewater sewer over the years. The direct discharges of wastewater to the river also persist in all scenarios despite the efforts to increase the wastewater treatment capacity of the city. The treatment coverage is also negatively affected by the infiltrations. The newly installed systems could have the capacity to treat 83% of the generated wastewater in scenario 2011 but considering infiltrations taking place, the treatment coverage decreases to 60%.

An important conclusion of the plausibility analysis is that the total water inputs to the sewer may be largely underestimated. The additional water volume originates most probably from larger wastewater contributions from the industry and NI/ND Users and from larger or additional sources of Permanent and Seasonal Infiltration.

As a consequence of the suspected higher total input to the sewer, the sewer performance presented in section 4.3.4 should be considered as conservative calculations. The impact of a larger total input to the sewer is translated into larger volumes at the Sewer Export flow, at the Wastewater Exfiltration flow and at the Direct Discharge flow from the WW Sewer. Another consequence of a larger total input to the sewer would be an even lower wastewater treatment coverage.

The comparison of the 2030 scenario to the subscenarios for dry and rainy conditions (Figures 4.9, 4.10, 4.11) leads to the conclusion that the nutrient import and export routes are not significantly affected by the total water imports to the city. Therefore, even under conditions of a larger water input to the sewer, the total amount of N and P reaching the river and the soil would remain almost unchanged. However, the N and P concentration in the flows downstream the WW Sewer decrease, including the inputs to the WWTPs. This facilitates the fulfilment of the discharge limits set by the Mexican guidelines. It is controversial, whether the achievement of the discharge limits by means of dilution is a positive aspect.

In conclusion, the basic scenarios should be considered as a first iterative step needed in the integral evaluation of the WWMS of Tepic. They are useful for the identification of the current trends as well as for the detection of topics needing further detailed research.

Among the issues requiring further research, following were identified as priorities: the assessment of the total wastewater generation of the Industry and NI/ND Users and the assessment of the infiltration rate to the WW Sewer. These factors were identified as being primary for continuing the integral evaluation and to complete an accurate MFA of the WWMS in Tepic.

Chapter 5

Detailed asssesment 2011

5.1 Preliminary test

In the previous section 4 it was established that the plausibility criteria applied to the outflows of the sewer were not met. It was also established that the most likely explanation was that the total water inputs to the sewer were underestimated. Before proceeding with a more detailed calculation of the system, a test was made to find out whether the differences in the nutrient concentrations shown in Figure 4.14 and in Table 4.9 could be explained by the monthly precipitation variations and by differences in the dilution patterns of the different sewer outputs. The information available about the WWMS at Tepic from 2003 to 2012 was obtained from various sources. In order to carry out a simulation for the most appropriate year and to maximize the data use, it was necessary to classify and evaluate the available data. The approach taken to maximize the use of the incomplete data sets is found in Espinosa Gutiérrez and Otterpohl (2014). A summary of the approach is explained in the next paragraphs.

The available data was classified in flows or concentrations that are subjected to significant variation due to variations in the precipitation (rain-dependent and rain-independent categories). Secondly, for the rain-dependent data, two subcategories were defined to distinguish data related to dry and to rainy periods. Table 5.1 presents a summary of the categorization of the available data.

After analysing the changes in the frame conditions and infrastructure over the years, it was decided that, except for the mass transfer coefficients (TC) and the capacity at WWTPs, all the rain-independent information and the information for dry periods could be used for any other year under consideration of applicable scale factors (e.g. population growth for the drinking water demand). In order to maximize the data use while providing an actual view of the status in the city, the year 2011 was selected as optimal for a detailed scenario.

Table 5.1: Classification of available data with indication of reference year and source type

Category	Available information (year)	Source
Rain independent data		
	Water consumption of all users (2007, 2009, 2012)	a
	Hydraulic capacity of the WWTPs (2007, 2009, 2011)	a
	Direct wastewater discharge from industrial and non-industrial/non-domestic users (2007, 2012)	a
	N concentration in drinking water and groundwater (2007, 2010)	a
	Mass transfer coefficients at processes (2007, 2011)	a,b
	Population (2007-2012)	c
	Coverage of the public services for water supply and waste water disposal (2007, 2011)	a,b
	City characteristics: size, sealing degree, type of sewer, condition of sewers (2007, 2011)	a,b,c
Rain dependent data		
	Annual and monthly precipitation (2007, 2008, 2009, 2011, 2012 and historical average from 1977 to 2012)	c
	⇒ *Measured in dry season*	
	Nitrogen and phosphorus concentration in the influent of the WWTP (2006, 2007, 2008)	a
	Nitrogen and Phosphorus concentration at the direct discharge of the sewer (2003, 2008)	a
	⇒ *Measured in rainy season*	
	Nitrogen and Phosphorus concentration inside the sewer pipelines of a residential area (2011)	d

Sources:
a: Information obtained from the registries of the local waterworks operator and from the water authorities.
b: Information obtained by means of expert consultation.
c: Information obtained from the INEGI.
d: Information obtained by means of a measurement campaign in cooperation with the local university.

To account for the monthly rain variations, the model was adjusted to be processed in 5 periods (instead of 1 period as previously set for the basic scenarios). The first four periods were used to represent the months from June to September, which correspond to the rainy season. The fifth and last period was used to represent an average month of the dry season. Additionally, a set of equations was developed to describe the nutrient concentrations at the outputs of the sewer. The concentration of the undiluted domestic wastewater was considered to be equal to the concentration of the sewer exports. Then, the concentrations observed at the entrance of the different WWTPs were used to generate further equivalence equations for the other sewer outputs. Equations 5.1 to 5.5 describe the empirical equivalences found between the undiluted domestic wastewater and the sewer outputs. These equations were applied to all periods of the model under the assumption that the dilution patterns remain unchanged in the dry and rainy season. These equations were used to account in the model for the variations in the dilution patterns at the outputs of the sewer.

Where $C_{i,j}$ = Concentration of substance i in flow j:

$$C_{Ntot,SewerExport} = 1 \cdot C_{Ntot,HouseholdsWastewater} \tag{5.1}$$

$$C_{Ntot,DirectDischarge} = 1 \cdot C_{Ntot,WWtoPunto} \tag{5.2}$$

$$C_{Ntot,WastewaterExfiltration} = 2 \cdot C_{Ntot,WWtoPunto} \tag{5.3}$$

$$C_{Ntot,WWtoCantera} = 1.46 \cdot C_{Ntot,WWtoPunto} \tag{5.4}$$

$$C_{Ntot,WWtoForum} = 1.23 \cdot C_{Ntot,WWtoPunto} \tag{5.5}$$

The equations were developed based on information found in the design documents of the WWTPs, on a measurement campaign to wastewater samples from the sewer (Espinosa Gutiérrez et al. 2015), on the obtained concentration at the flow Households Wastewater from scenario 2011 and on discussions with local experts.

No data was obtained regarding the P content in the groundwater or the drinking water in Tepic. Furthermore, the P concentrations observed at the outputs of the sewer presented a different dilution pattern than that of the observed N concentrations. Since the information on the N content of the flows was more abundant and the N measurements were considered as more reliable, it was decided to continue the MFA without the P layer of the model.

Equations 5.1 to 5.5 were implemented in the new model periods and a simulation was run. The results of the N concentrations at the outputs of the sewer in this first preliminary test are shown in Figure 5.1. The modelled concentrations differ from the reference concentrations for Wastewater Exfiltration (measured in the rainy season) and from the reference concentrations at the inflow of the WWTPs (measured in the dry season): all of the modelled concentrations presented higher concentrations. Furthermore, some of the calculated concentrations at the outputs of the WW Sewer were higher than that of the undiluted domestic wastewater. This situation is not plausible given that a sewer normally does not function as a concentrating process.

Therefore, it was concluded that the differences between the modelled concentrations at the outputs of the sewer and the reference values could not be explained solely by variations in the rainfall or by the differences in the dilution patterns. An additional water input is required to explain the dilution of N in the flows.

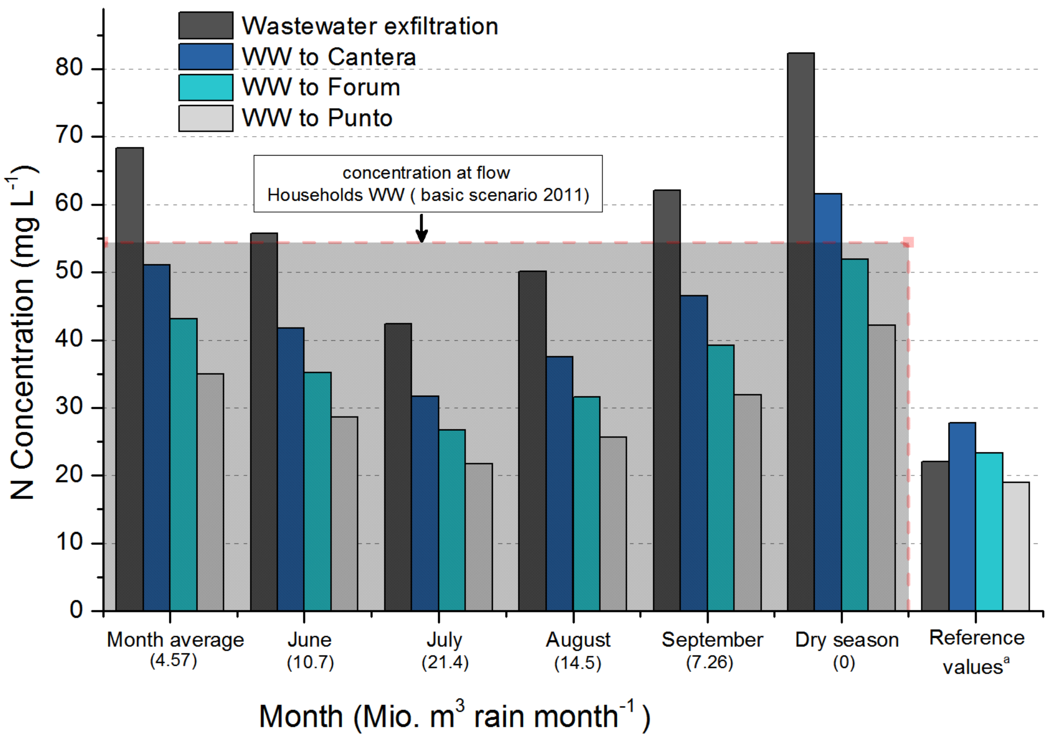

Figure 5.1: N concentration at the outputs of the sewer in the preliminary test.
[a]The reference values for the flow Wastewater Exfiltration apply for the rainy season. The reference values for all other flows apply for the dry season.

5.2 Further model adjustments

To complete the MFA of the system, an additional import flow was added to the process WW Sewer. This flow was named Additional Water Inputs (AWI). Three important considerations were made:

- There are no additional nutrient sources.
- Most of the additional water imports to the system originate from infiltration of rain or groundwater into the sewer, and
- The water quality of the Additional Water Inputs is equal to groundwater quality.

Furthermore, in order to to refine the simulations, the export flow named WW to Delicias was added to represent the flow of water towards the WWTP Delicias. The process WWTP Delicias itself was not added because this treatment facility was not in operation by 2011. A new equation was required to describe the expected N concentration in this flow (Eq. 5.6).

$$C_{Ntot,WWtoDelicias} = 1.8 \cdot C_{Ntot,WWtoPunto} \tag{5.6}$$

The calculation of the AWI flow in the model was based on the total N input to the WW Sewer and on the reference N concentrations which were measured in the outflows of the WW Sewer: the model calculates how large the AWI flow should be in order to dilute the total N input to the WW Sewer so that the concentrations observed in the reference measurements are met. The reference measurements selected as input parameters for the model were: the N concentration in the Wastewater Exfiltration flow during the rainy season and, for the dry season of the model, the N concentration in the flow WW to Punto.

According to this calculation scheme, the flow AWI is proportional to the total N input to the sewer, given that the concentrations at the outflows of the WW Sewer are now fixed in the model as input parameters or by means of the Equations 5.1 to 5.6. A drawback was that the total N input to the WW Sewer is based on literature values. The actual N input may be larger or smaller. In order to calculate the minimum AWI flow and thus to remain in a conservative range, the minimum total N input to the WW Sewer should be used. For this purpose, the N input to the sewer from the main N sources (Households and NI/ND Use) was recalculated. This was done iteratively by means of several simulations with different N loads. The goal was to reach the minimum N necessary to obtain realistic N concentrations at the outputs of the sewer. By realistic concentrations it is meant that the N concentration at the Wastewater Exfiltration flow in the dry season (when the infiltration should be at its minimum) could be the same but not higher than the N concentration at the Households Wastewater. This assumption implies that the flow Wastewater Exfiltration is not being diluted during the dry season. The concentrations in all other sewer outflows are automatically lower as can be inferred from Equations 5.1 to 5.6.

Assuming that the wastewater from Households and NI/ND Use is very similar in composition, the recalculated N concentration in the Households Wastewater flow was then used as new N concentration for the NI/ND Wastewater flow. Additionally, some flows were reviewed and updated. The data on the precipitation was according to monthly amounts measured in 2011. The groundwater flow was recalculated based on the average domestic consumption rate obtained from the simulations of previous sections, on the most recent data on population number, service coverage, users distribution and known water losses. New information allowed also for an improved calculation of the evapotranspiration coefficient. The new and updated information fed to the model is shown in Table 5.2.

Table 5.2: New and updated parameters for the detailed evaluation of scenario 2011

Information	Value		Source
Precipitation, June 2011 (mm / Mio. m^3 $month^{-1}$)	192 / 10.7	(± 10%)	1 / Eq.4.2
Precipitation, July 2011 (mm / Mio. m^3 $month^{-1}$)	383 / 21.4	(± 10%)	1 / Eq.4.2
Precipitation, August 2011 (mm / Mio. m^3 $month^{-1}$)	259 / 14.5	(± 10%)	1 / Eq.4.2
Precipitation, September 2011 (mm / Mio. m^3 $month^{-1}$)	130 / 7.3	(± 10%)	1 / Eq.4.2
Precipitation in Dry Season 2011 (mm / Mio. m^3 $month^{-1}$)	0 / 0	(± 0%)	1
Population in 2011 (Inhabitants)	347,195	(± 3%)	2
Groundwater flow (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	5.25 / 63	(± 15%)	3
Bottled Water flow (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.076 / 0.91	(± 20%)	4
Decentralised Water Supply flow (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.028 / 0.33	(± 20%)	4
Industrial Private Water Supply (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.32 / 3.88	(± 20%)	4
Industrial Direct Discharge flow (m^3 $month^{-1}$ / m^3 $year^{-1}$)	285 / 3,420	(± 20%)	4
NI/ND Private Water Supply (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.44 / 5.24	(± 20%)	4
NI/ND Direct Discharge (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.015 / 0.18	(± 20%)	4
Wastewater to treatment plant Delicias (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.26 / 3.16	(± 10%)	4
N load in wastewater from households (g N inh^{-1} day^{-1})	7.5	(± 10%)	5
N concentration in NI/ND Direct Discharge and NI/ND Wastewater (mg L^{-1})	40	(± 10%)	5
N concentration in flow Wastewater Exfiltration (rainy season, mg L^{-1}, new parameter)	22.43	(± 10%)	6
N concentration in flow Wastewater to Punto (dry season, mg L^{-1}, new parameter)	19	(± 20%)	7
Evapotranspiration coefficient [TC for Stormwater to Unsealed Areas → Evaporation(2)]	0.74	(± 0%)	8

Sources:
1-INEGI 2012
2-Consejo Nacional de Población 2012. This is equivalent to a population growth of 14%.
3-Calculation based on the water consumption per capita obtained in basic 2007 scenario and on the service coverage and water losses in 2011 as communicated by SIAPA Tepic (see Annex A)
4-REPDA for year 2007 provided by CONAGUA Nayarit and REPDA for 2011 (CONAGUA 2012)
5-Obtained iteratively in this research. See explanations in section 5.2.
6-Espinosa Gutiérrez et al. 2015. The uncertainty of the mean was based on the raw data mentioned in the sources.
7-CONAGUA 2008a. The uncertainty of the mean was based on the raw data mentioned in the sources.
8-Calculated from INEGI 2013 and Servicio Meteorológico Nacional de México 2007. Calculations with help of the ETo Calculator of the FAO (FAO 2012)

5.3 Results and discussion

The results of the detailed evaluation for the year 2011 represent the final MFA for the city. They are also helpful to evaluate the system under dry and rainy conditions in the same year instead of comparing the system on a yearly scale as in the basic scenarios. This section presents the main results obtained in the detailed 2011 scenario and discusses the differences on the indicators observed for the dry and rainy conditions with special emphasis on the impacts of the newly added AWI flow over the system. The results of the MFA for all flows and layers as obtained in STAN are included in Annex A for a month within the rainy season and for the dry season.

The inclusion of the AWI flow in the system affects the overall mass balance, the evaluation of the sewer performance and the concentrations of the nutrients downstream the WW Sewer. The water consumption per capita as well as the water consumption and wastewater generation patterns of the basic 2011 scenario (Section 4.3.3 and Section 4.3.2) remain unaltered in the detailed 2011 scenario.

5.3.1 Nitrogen input from Households and NI/ND Use

The calculated AWI flow depends directly on the total N input to the sewer. The largest N contribution to the sewer originates from Households followed by NI/ND Use. Both values were optimized by means of iterative calculations as explained in the Section 5.2.

The calculated N input from Households was 78 tonnes month^{-1} which corresponds to 7.5 g N inhabitant day^{-1}. With the calculated load and according to the water input to the process Households, a concentration of 39 g N L^{-1} in domestic wastewater is obtained. Under the consideration that wastewater from the NI/ND Use process has an N concentration similar to that of domestic wastewater, a concentration of 40 g N L^{-1} was applied to the flow NI/ND Wastewater and NI/ND Direct Discharge. An uncertainty of $\pm$ 10% was assumed for both values. Additionally, the newly calculated per capita N load was also applied to the process Decentral Sanitation and a total N input of 1.58 tonnes month^{-1} was obtained.

5.3.2 Sources and disposal routes

Water

The sources and disposal routes were previously categorized in the evaluation of the basic scenarios (section 4.3.1). Figure 5.2 summarizes the water imports and exports for the months from June to September (rainy season) and for a month of the dry season.

The newly calculated AWI flow represents an increase in the total water imports to the system equivalent to 71-75% of the groundwater imports in the rainy season and to 27% in the dry season. Regarding the water exports, the dissipation of water and the exports via WWTPs do not differ between different seasons. However, the clean water exports and the exports of the Stormwater Sewer differ significantly between the rainy and the dry season due to variations in monthly precipitation. Additionally, the sewage exports increase by more than 150% during the rainy season compared to the values in the dry season. This is due to the Seasonal Infiltration and AWI flows entering the WW Sewer during the rainy season.

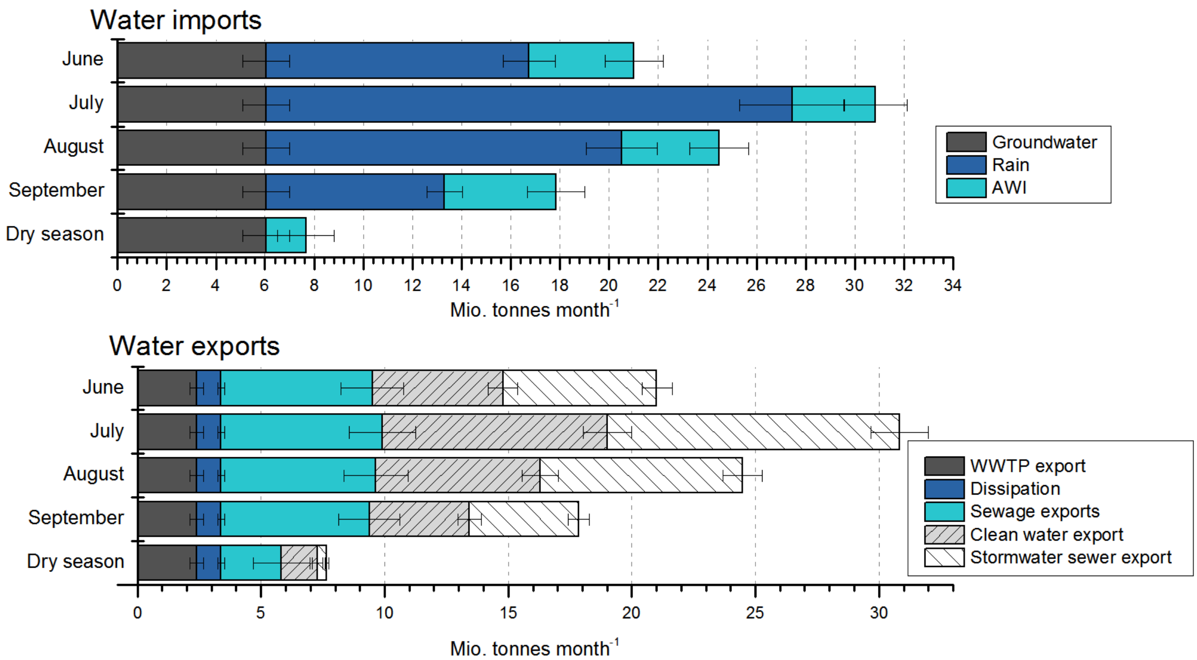

Figure 5.2: Monthly water balance in detailed scenario 2011 according to sources and disposal routes.

Nitrogen

The N imports by the newly added AWI flow are minimal in comparison to the other imports to the system. Summarizing the N contained in the Groundwater flow and in the Food and Chemicals Supplies flow together as a basis for comparison (hereafter named "basic N imports"), the AWI flow represents an increase of 2% in the dry season and of 5-7% in the rainy season. Figure 5.3 shows the summary of the N imports and exports according to source and disposal route.

The N balance is affected more significantly by the rain than by the AWI flow: in the rainy season, the N import from the sealed areas due to pollution carried from city surfaces represents an additional N input of 13-38% on top of the basic N imports. The basic monthly N imports are 129 tonnes. In July, the most rainy month, the total N imports are 185 tonnes. This is 56 tonnes larger than in the dry season. The additional N input originates mostly from sealed surfaces.

The export of N through the Stormwater Sewer increases largely during the rainy season (up to 300% compared to dry season) and the N in the sewage exports increases in average 34% compared to amounts in the dry season. On the other hand, the export of N through the WWTPs is reduced by 41% in the rainy season.

Figure 5.4 shows the N exports to different destinations in the environment. It is observed that the export of N to the surface water is always larger in the rainy season than in the dry season, in average 46% larger. The exports of N to the soil and groundwater remain relatively constant over the year. Denitrification represents a negligible N sink.

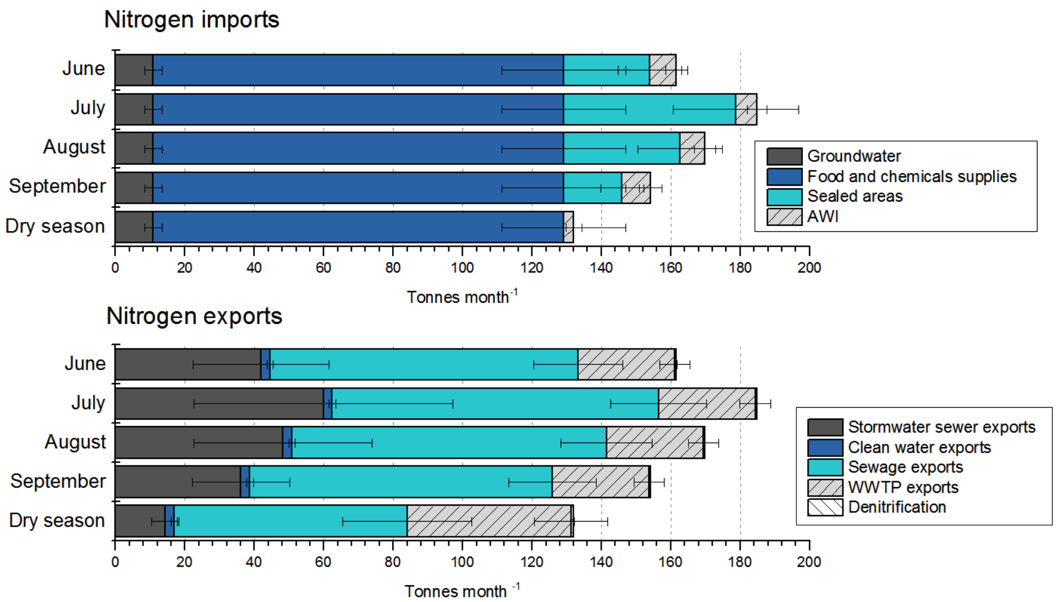

Figure 5.3: Monthly nitrogen balance in detailed scenario 2011 according to sources and disposal routes.

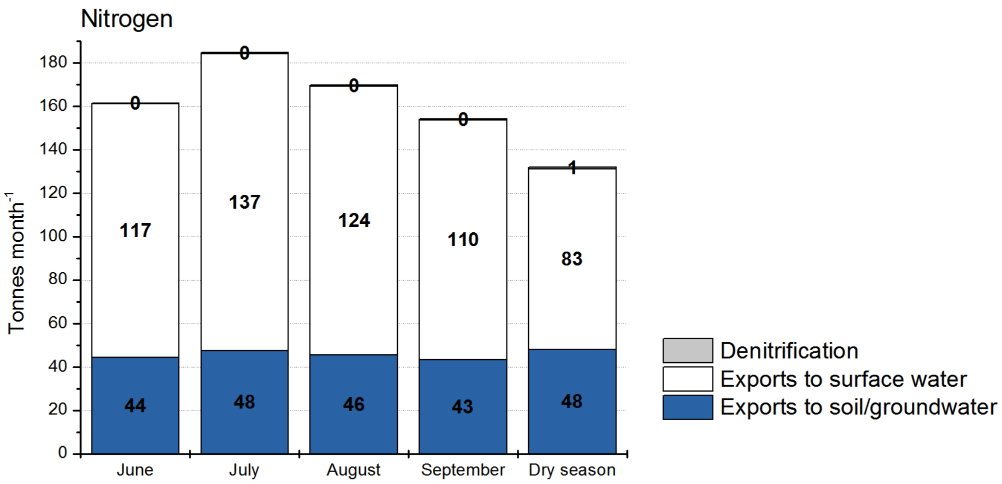

Figure 5.4: Nitrogen exports to the environment in detailed scenario 2011.

5.3.3 Sewer performance

Infiltration to the sewer

The term total infiltration is used in this research as a synonym for undesired or unplanned Infiltration and Inflows (I/I) of water to the sewer. In this detailed scenario, the total infiltration to the sewer Q_{inf} is calculated by adding the flows Permanent Infiltration, Seasonal Infiltration and AWI. The ratio Q_{inf}/Q_{ww} is then used to estimate the Additions by Infiltration or AI, as shown in Equation 4.7. The results indicate an average infiltration rate of 191% during the rainy season and of 62% in the dry season. From this, an annual average infiltration rate of 105% was calculated. Table 5.3 shows the infiltration amounts and rates in detail.

Table 5.3: Infiltration in the detailed scenario 2011

	Infiltration (in Mio. tonnes)		Additions by Infiltrations (in %)	
June	5.95	± 1.19	187%	± 42%
July	6.38	± 1.31	201%	± 46%
August	6.10	± 1.23	192%	± 43%
September	5.81	± 1.16	183%	± 41%
October (dry season)	1.99	± 1.22	62%	± 37%

The I/I can be also compared to the total volume in the sewer instead of being compared to the sewer inputs. This comparison can be then considered equivalent to the German infiltration indicator called Infiltration Share (IS, in German *Fremdwasseranteil*). The calculation of the Infiltration Share is indicated in Equation 5.7, where Q_{inf} is the total infiltration volume and Q_{ww} is the wastewater input to the sewer.

$$Infiltration\ Share = \frac{Q_{inf}}{Q_{inf} + Q_{ww}} \cdot 100\% \qquad (5.7)$$

The calculated infiltration share in Tepic is 65% on average in the rainy season and 38% in the dry season. In other terms: in the rainy season two thirds of the water in the sewer are not municipal wastewater. In the dry season, only a third of the water in the sewer corresponds to infiltration. The shares of wastewater and I/I in the sewer as calculated for the dry and rainy season are shown in Figure 5.5.

There is no clear regulation in Mexico regarding the maximum allowed infiltration to the sewer. Although infiltration is known to take place, the applicable guidelines found in the MAPAS state clearly that the sewer network should be constructed as an hermetic system and that any water volume caused by infiltration or exfiltration is not considered in the planning (CONAGUA 2007).

In Germany, there is no maximum infiltration amount neither. However, the German Wastewater Levy Law (*Abwasserabgabengesetz*, AbwAG) states clearly that it is not allowed to meet the pollutant discharge limits for wastewater discharges by means of dilution. In several German federal states, such as Baden-Württemberg and Bavaria, it is a common practice to increase the wastewater discharge fees when the yearly average IS during dry periods amounts to 50% or more (Lucas 2004, Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg [LUBW] 2007).

Compared to the average precipitation in the rainy season, which is 13.5 Mio. m^3, the infiltration is equivalent to 51% of the total precipitation entering the WW Sewer. However, a small percentage of the total infiltration is originated by the losses in the drinking water system (Permanent Infiltration). Figure 5.5 shows the relevance of each single component for its impact on the total volume in the sewer. It can be seen that the Permanent Infiltration flow plays only a small role in the overall infiltration.

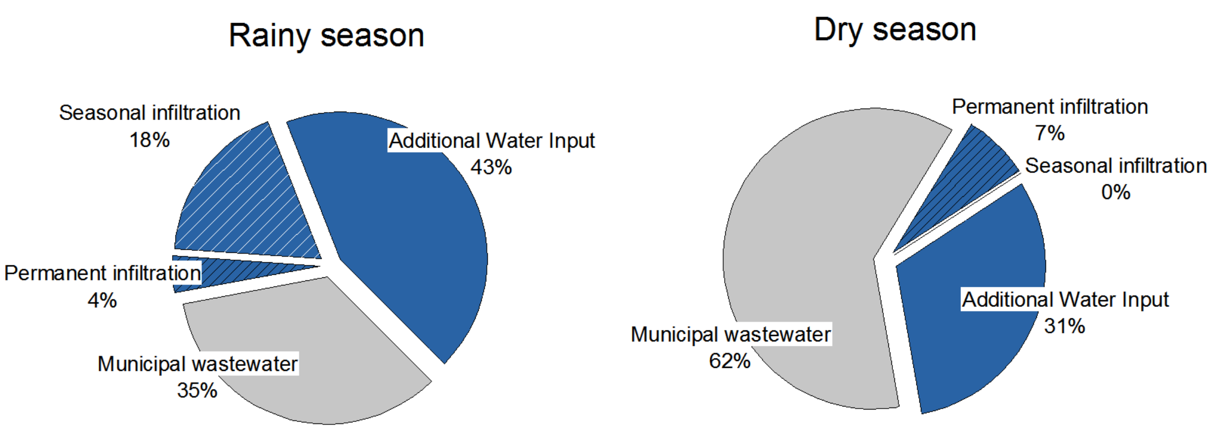

Figure 5.5: Composition of the water in the sewer in the rainy and dry seasons

Discharge of untreated wastewater

The discharge of raw wastewater from the WW Sewer takes place through three routes:

1. The Sewer Export to the Stormwater Sewer (eventual discharge to river),
2. The Wastewater Exfiltration (discharge to soil and groundwater), and
3. The Direct Discharge from the WW Sewer (discharge to river).

The results of the detailed scenario for 2011 indicate large differences in these discharge flows during the rainy and dry seasons with respect to both water and nitrogen flows (Figure 5.6). Regarding the water flows, the most significant difference is the increase of the flow Direct Discharge in the rainy season: it increases from 1.38 Mio. tonnes month^{-1} to 4.55 Mio. tonnes month^{-1} representing a 300% increase in the rainy season.

The N load of the raw sewage flows follows a similar pattern. All flows are increased during the rainy season and the N load at the Direct Discharge increases most from 26 tonnes in the dry season to 51 tonnes in the rainy season. This is a difference of 100% between the seasons. The N load in the flow Wastewater Exfiltration is very similar in both seasons although the volume of the flow does increase largely. This is explained by the dilution of the N concentration caused by the AWI flow in the sewer (the AWI flow is a large water volume with low N concentration).

It is also observed that the uncertainty of the nitrogen flow in the Direct Discharge flow is much larger in the dry season than in the rainy season. This is due to the uncertainties in the input information which are also larger in the dry season.

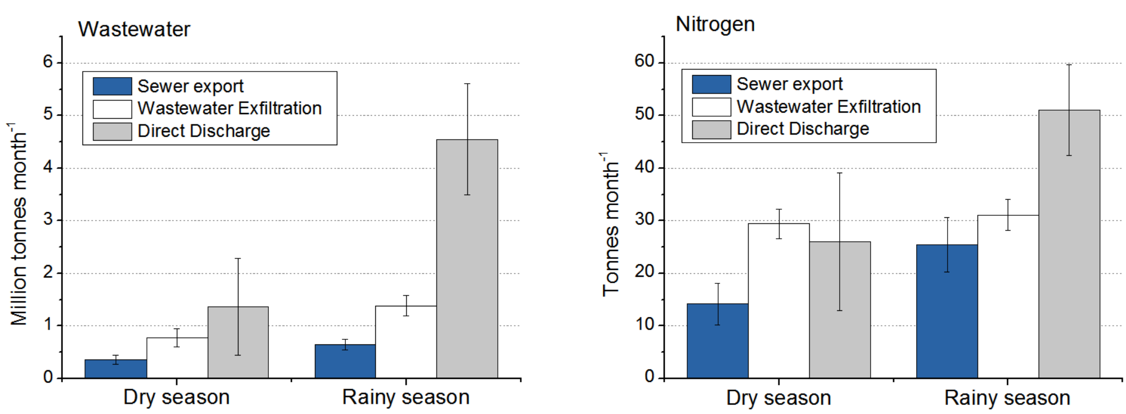

Figure 5.6: Water and nitrogen in untreated wastewater flows from detailed scenario 2011.

Secondary treatment coverage

As explained in section 4.3.4, this indicator compares the sewer inputs to the installed secondary treatment capacity in order to calculate the coverage of the secondary treatment of wastewater in the city. The obtained results indicate a treatment coverage of 35-69% during the dry season, when the infiltration is lowest. During the rainy season, the calculated coverage decreases to 21-33%. In a scenario without any infiltration, the treatment coverage would be minimum 66% and maximum 88%. Figure 5.7 shows a graph with the calculated minimum, average and maximum treatment coverage for each season and for a scenario without I/I.

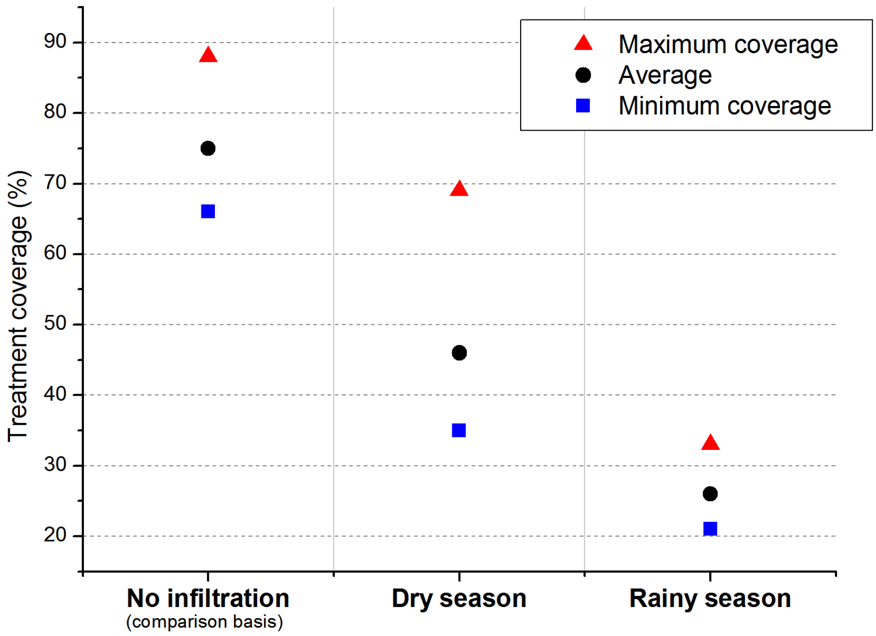

Figure 5.7: Secondary treatment coverage in detailed scenario 2011.

Figure 5.8 classifies the impact of sewer infiltration on nitrogen masses reaching a WWTP. The results demonstrate that under a scenario without infiltration, the maximum amount of N reaches a WWTP. As the infiltration increases, the amount of N arriving a the WWTP decreases. As previously inferred in Figure 5.6, Figure 5.8 demonstrates that the I/I to the WW Sewer generates a dilution of the N leading to less N reaching the WWTPs and more N leaving the system through untreated wastewater flows.

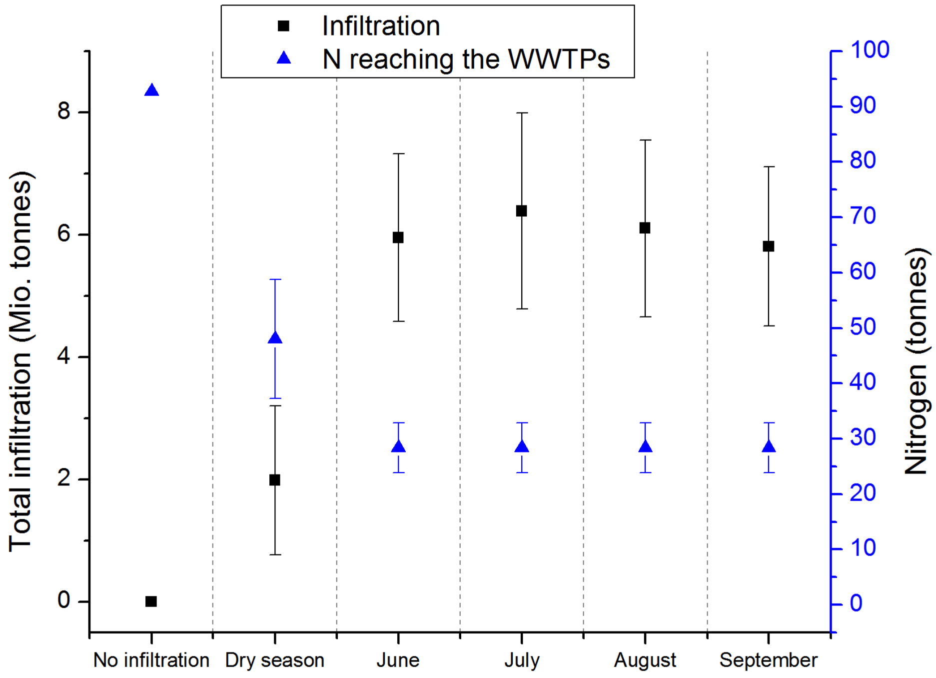

Figure 5.8: Monthly infiltration and nitrogen masses arriving at the wastewater treatment plants. WWTPs = wastewater treatment plants

5.3.4 Nitrogen in the export flows

In terms of pollution, the relevant export flows from the system are those of wastewater. There are wastewater export flows from the WWTPs (treated) and from the Stormwater Sewer (untreated) as well as export flows of untreated wastewater through direct or diffuse discharges of the different users in the city. Normally, the untreated wastewater flows from domestic sources contain N in the form of Ammonia and organic N compounds such as proteins and urea. In treated flows, the predominant N form is nitrate. The treated form of the N is damaging the aquatic environment in terms of toxicity to a lower extent. However, it contributes to the undesired eutrophication of water bodies (Schwedt 2001).

Figure 5.9 shows the N concentrations of all relevant export flows for the rainy and the dry season. Additionally, it shows the corresponding monthly N mass flow including N leaving the system with the sludge flows from the WWTPs. The concentrations at the Polluted Stormwater Sewer Discharge vary largely from month to month. These are presented separately in Figure 5.10.

Figures 5.9 and 5.10 show that the Mexican wastewater discharge limits for the protection of aquatic life (15 mg N L^{-1} according to NOM-001-SEMARNAT-1996) are exceeded in several export flows in both the rainy and the dry season. The Decentral WW Emissions flow represents the highest N concentration (79 mg N L^{-1}). However, its monthly mass flow of 1.63 tonnes N $month^{-1}$ represents less than 1% of the total N exports of the city. The NI/ND Direct Discharge and the Industrial Direct Discharge have similar characteristics.

In this thesis, the term "critical flow" is used to refer to a flow exceeding the mentioned Mexican discharge limits and/or representing 10% or more of the total N export (in terms of mass flow). Applying these criteria it can be observed in Figures 5.9 and 5.10 that during the rainy season the critical flows are the Wastewater Exfiltration, the Direct Discharge, the Stormwater Sewer Discharge and the Polluted Stormwater Sewer Discharge. The discharge of the WWTP Punto (the largest WWTP in the city), and the sludge flows (all sludge flows together) are also important N export routes during the rainy season. However, they represent less than 10% of the total exports.

In the dry season the critical flows are the Wastewater Exfiltration, the Direct Discharge, the Discharge WWTP Punto, the Polluted Stormwater Sewer Discharge and the sludge flows. It can be concluded that, in comparison, there are fewer flows exceeding the discharge limits during the rainy season. However, the total N mass flow is increased in several of the flows within the rainy season as well (e.g. the Direct Discharge flow, Wastewater Exfiltration and Polluted Stormwater Sewer Discharge).

It was observed that the N export through untreated flows is always larger than the N export through treated flows and that it also increases largely in the rainy season. For example, the total export of untreated nitrogen in August is 136 tonnes month^{-1} and the export of treated nitrogen is 28 tonnes month^{-1} (yielding a total export of 164 tonnes month^{-1}). During the dry season, the total export of untreated nitrogen is 81 tonnes month^{-1} and the treated nitrogen export is 41 tonnes month^{-1} (total export is 122 tonnes month^{-1}).

The difference in the monthly totals is explained by the reduced N import from sealed areas during the dry season. The decrease on N exports with treated wastewater during the rainy season is explained by the dilution effect induced by an enlarged total water volume in the sewer due to increased AWI flow and rain. This dilution reduces the total amount of N reaching a WWTP.

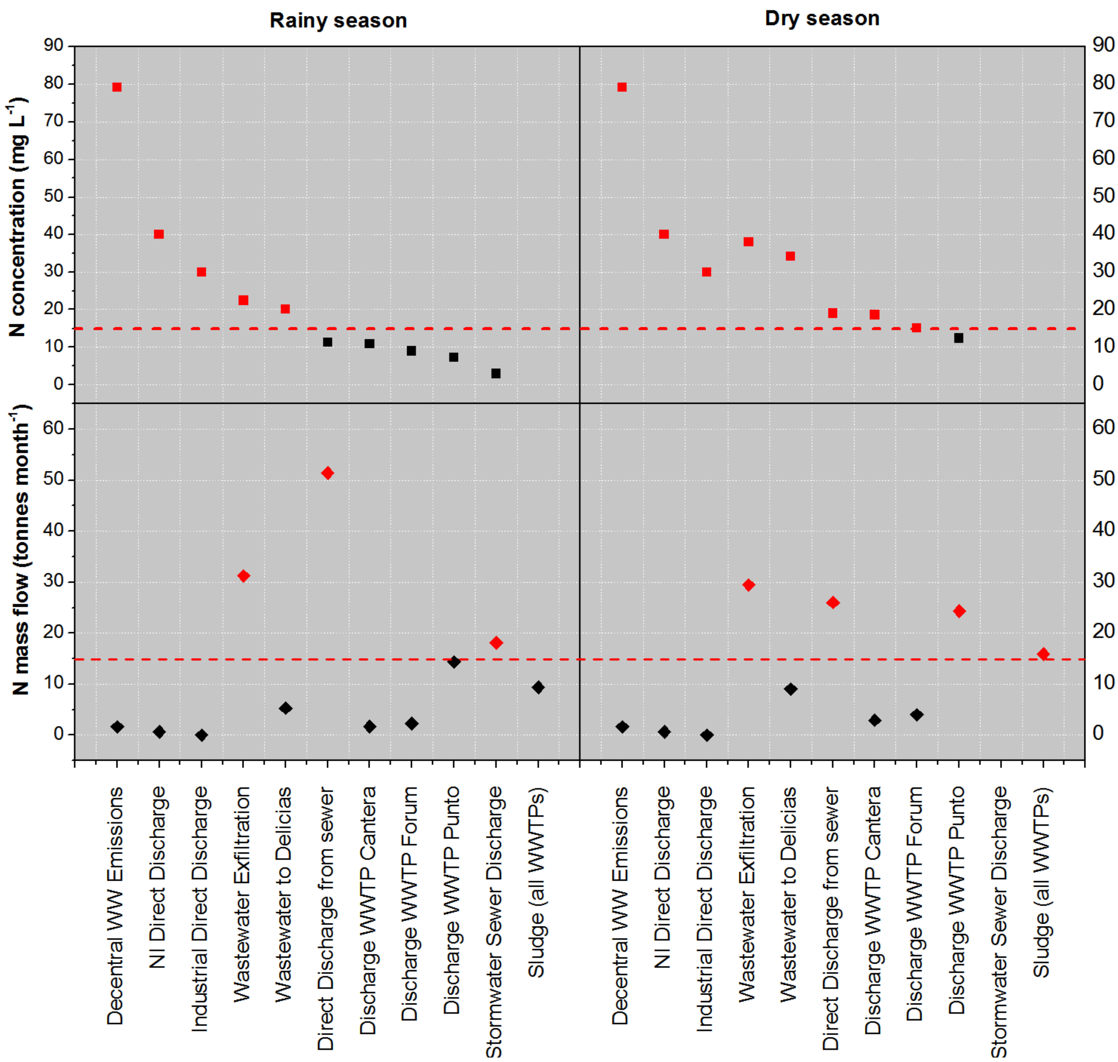

Figure 5.9: N concentrations and N mass flows in different export flows.
Upper graphs: the flows above the dotted line exceed the Mexican maximum limit for the protection of aquatic life.
Lower graphs: the flows above the dotted line represent more then 10% of the total N mass exports.

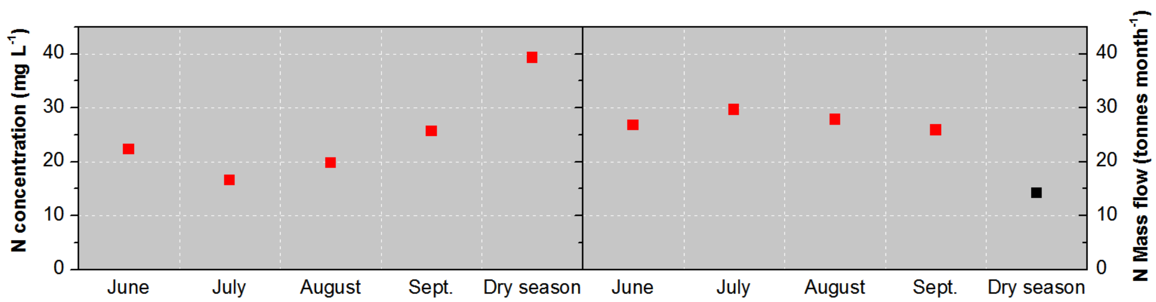

Figure 5.10: N concentrations and N mass flows in Polluted Stormwater Sewer Discharge.
Graph on the left: the flows above the dotted line exceed the maximum limit for the protection of aquatic life.
Graph on the right: the flows above the dotted line represent more then 10% of the total N mass exports.

5.4 Plausibility analysis

The plausibility of the flows upstream the sewer was already successfully analysed in section 4.4. In this section the flows downstream the sewer are tested for plausibility. Two criteria were chosen: the N load per capita and the total infiltration to the sewer.

In the detailed monthly scenario for 2011, the nitrogen input from Households was recalculated and a value of 7.5 g N inhabitant day^{-1} was obtained. This was compared to the N load reported in literature for another Mexican city. Values reported for Brazil, Turkey and for Latin America are included in the comparison under the assumption that the domestic consumption habits and pollution trends might be similar to those in Mexico. Literature values for USA and Europe were also consulted. Figure 5.11 presents the results of the comparison.

The value obtained in this research lies whithin the reported values for Mexico, Latin America and Europe. It is also very close to the minimum reported values for the other consulted countries. The conclusion drawn from the analysis is, that the calculated value is plausible and that it can be considered as a conservative (low) value.

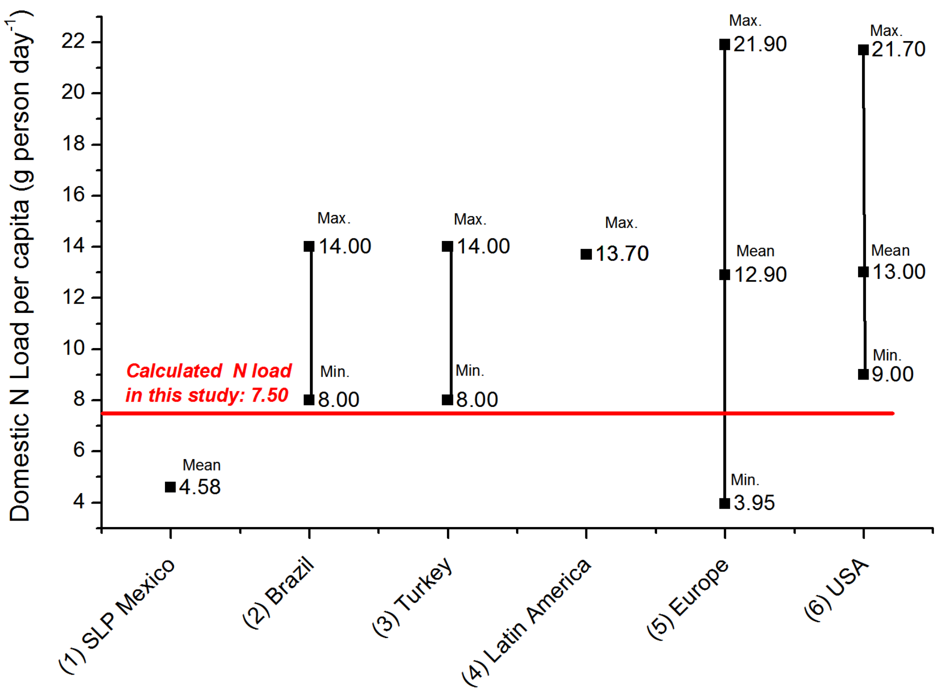

Figure 5.11: Plausibility test for the N load.
Literature sources: (1) Martinez et al. 2011, (2),(3) and (6) Tchobanoglous et al. 2003, (4) Foster et al. 1987, (5) DWA 2008.

The second plausibility criteria is the infiltration rate to the sewer. Literature values for sewer infiltration in Mexico or Latin America were not found. Therefore, a general comparison with the results of infiltration studies in Germany was made. The infiltration rate in old networks, which are not regularly inspected and not preventively maintained (such as those in Tepic), can be expected to be higher than in more recently and properly inspected and maintained networks.

A study of the German Association for Water, Wastewater and Waste (*Deutsche Gesellschaft für Abwasserwirtschaft, Abwasser und Abfall*, DWA) carried out in 2009 and investigating 41,691 km[1] of sewer networks in Germany, mentions that 79% of the interviewed municipalities reported to have an infiltration to the sewer equivalent to 33% or less (infiltration expressed as AI). A share of 20% of the interviewees reported more than 33% of infiltration. This data refers to the infiltration in dry periods. The average age of the pipelines was 41 years. In the same study, only 20% of the pipeline sections were described as having a critical condition requiring immediate or mid-term rehabilitation measures (Berger and Falk 2011).

Earlier studies of the DWA about the condition of sewer networks in Germany (Berger and Lohaus 2005, Berger et al. 2002) do not mention the infiltration rate to sewers in former years. However, the results indicate that the the topic of regular network inspection and maintenance has gained importance over the years. For example: whereas in 2001 only 30% of the sewer network had been inspected, by 2004 already 80% had been inspected (Berger and Lohaus 2005). The inspection rate was the same in 2009. Furthermore, the data on sewer age distribution reported by Berger and Lohaus (Berger and Lohaus 2005) show a positive development in Germany with increasingly younger pipeline networks.

The study carried out by Lucas (2004) on numerous sewer networks and WWTPs in the federal state of Baden-Württemberg mentions an average yearly infiltration rate (AI) in 1998 of 42% in areas with strictly separated sewers, 58% in areas where the type of sewer is mostly separated (> 50% separation), 70% in areas where the type of sewer is mostly mixed (> 50% mixed) and 67% in sewers with strictly mixed networks. These are averages measured at the influents of 1158 WWTPs. A detailed look at the raw data for the average figures reveals numerous WWTPs whose average yearly infiltration rate (AI)is between 100% and 200%.

Comparing the infiltration rates in 1998 reported by Lucas (2004) and the infiltration rates for 2009 reported by the DWA (Berger and Falk 2011), it might be assumed that the infiltration to sewers in Germany was decreased over the years due to reconstruction of old networks, to the increase of inspection rates and to improved maintenance practices.

The sewer pipelines in Tepic have an average age of more than 40 years (state 2009) and the general condition of the network is poor (description in section 3.3). According to observations and information received during the site visits in Tepic, regular preventive channel and pipeline inspections are not carried out. The maintenance of the sewer network is done in a corrective manner. The

[1]represents about 10% of the total installed pipeline network according to Statistisches Bundesamt(2013)

yearly average infiltration rate (AI) calculated in this study is 104%. This seems plausible for an old and poorly maintained sewer network.

The results obtained in this study also revealed that infiltration in dry periods was 62% and 191% in rainy periods. Brombach (2002) states that the seasonal differences of the infiltration can be in a ratio of up to 1:10. Lucas (2004) presents the results of infiltration measurements from 1997 to 2000 at a WWTP in Baden-Württemberg demonstrating large seasonal differences with monthly infiltration rates varying from 0% to 600%. Hahn and Fuchs (2002) measured the infiltration at a WWTP in Unteröwisheim (also in Baden-Württemberg) between 1999 and 2001 and obtained results of monthly infiltration rates of 150% - 400%. Compared to the mentioned studies, the results of the present research for the infiltration in dry and rainy periods seem to be plausible and also seem to remain in a conservative range given the conditions of the network.

5.5 Conclusions

The preliminary tests of the detailed scenario 2011 demonstrated that an additional water input (AWI flow) to the system was required to explain the observed dilution of N in the outflows of the sewer. The scenario 2011 was adjusted to allow for the calculations of the AWI flow. This flow was linked directly to the total N input to the sewer. For a conservative calculation of the AWI flow, the minimum total N input to the sewer was recalculated iteratively. This allowed for an MFA for year 2011 considering the minimum realistic N input to the sewer.

The results of the detailed evaluation for 2011 show large differences between the seasons. It was observed that the water imports and exports in the rainy season could be up to 4 times larger than in the dry season. This difference is caused by an increase in rain and AWI flow in the rainy season generating an increase in the clean water exports, the Stormwater Sewer exports and also in the different sewage exports. These last exports are problematic because they are flows of untreated wastewater to the environment. They represent an average of 6.2 Mio. m^3 per month in the rainy season and 2.4 Mio. m^3 per month in the dry season.

The N balance proved that N imports and exports are not as largely affected by rain and AWI flow although their impact was also significant. The difference between the dry and rainy season on total N balance was up to +40% in the rainy season when the rain entering the WW Sewer carries pollutants from sealed areas.

By comparing total water and nitrogen inputs it was observed that with increased total water input to the system, more N is discharged through untreated flows and less N is conducted to a WWTP. The monthly N exports in the dry/rainy season are (in tonnes month^{-1}): sewage exports 67/90, Stormwater Sewer exports 14/46, WWTP exports 47/28.

Nevertheless, given that the WWTPs in Tepic are not eliminating a significant amount of N by denitrification or any other method (elimination was less than 1%), in both dry and rainy seasons the main final destination of all N exports is a surface water body (63% in the dry season and 73% in the rainy season). The remaining N is discharged to the soil or to the groundwater.

Regarding the sewer performance, several problems were identified. A significant infiltration to the sewer with strong seasonal variations was detected. Due to a high I/I over the year, the WW Sewer in the city behaves like a combined sewer instead of a separated sewer. Besides the large direct discharges which have been mentioned above, this may be a problem because the WWTPs have been designed and constructed for a separated sewer with inputs only from municipal wastewater and because the WWTPs are not equipped with adequate flow control or equalization measures at the inlet of the facilities.

According to the modelled conditions, the wastewater treatment coverage in the dry season is only 46% and in the rainy season it decreases even to 26%. The theoretical treatment coverage would be 75% under conditions of no infiltration.

The I/I has also an influence on the N concentrations of the outflows of the WW Sewer. During the rainy season, the N concentration in the outflows is diluted. Although this represents the fulfilment of the maximum discharge limits for some of the flows, it also represents an increase of the total N reaching the environment without treatment. Thus, the I/I is responsible for an increased export of organic N compounds and ammonia to the environment, which are toxic for the aquatic milieu.

Even after considerable efforts to improve the wastewater management in previous years, in 2011 the city still represents an important pollution source to the environment. This is mainly due to inefficiencies of the sewer network and to lesser extent due to a lack of nutrient removal schemes at the wastewater treatment facilities.

Chapter 6

Detailed projections for 2030

The next step in the MFA of the city of Tepic was to make projections of the water and wastewater situation in Tepic by 2030. This is useful to recognize the future challenges under consideration of the known trends and of the planned improvements in the WWMS of the city (improvements are described in Table 3.2).

6.1 Adaptations to model and input data

The detailed scenario for 2030 was based on the detailed model for 2011 but with some adaptations. Only two periods were included in the model: one to represent the average monthly flows in the rainy season and another one to represent the average monthly flows in the dry season.

The input data for both periods was a combination of the data used for the basic scenario 2030 and the detailed scenario 2011 as well as some data improvements. The new or updated information used for the detailed 2030 simulation is listed in Table 6.1. All other information remained as originally specified for the basic scenario 2030 and shown in Tables 4.2 to 4.5.

All previous equations were also applied to this model. However, in contrast to the detailed model for 2011, the N concentrations in the flows Wastewater Exfiltration and WW to Punto were not fixed as input parameters in the simulations. These concentrations had served for the purpose of calculating the AWI flow in the detailed scenario 2011.

For the 2030 scenario, another approach was taken to calculate the AWI flow. Amongst the planned improvements for the WWMS of the city (Table 3.2), the following measures can have an influence on the infiltrations to the sewer: reduction of water losses in the drinking water system, repair and continued maintenance of manholes, drains and slabs, and reduction of direct inputs of stormwater to the wastewater sewer from house roofs and paved house yards by connection of these streams to the Stormwater Sewer instead. These planned improvements, however, affect only the Permanent Infiltration and the Seasonal Infiltration flows. No improvements of the wastewater channels are planned and therefore, the AWI flow could remain unchanged or increase with growth of the city and ageing of the sewage system.

Based on the results of the AWI flow from the detailed 2011 scenario, two new equations were introduced to the model in order to specify the AWI flow in the detailed scenario 2030. It was assumed that the AWI flow responds to factors related to the wastewater channels and that the flow Households Wastewater can be used as an indicator of the growth of the wastewater channels.

Therefore, the AWI flow was set as a variable dependent on the flow Households Wastewater. Equations 6.1 and 6.2 show the new flow relationships implemented in the model. No further changes or adaptations were implemented in the model for the detailed 2030 scenario.

$$AWI_{rainyseason} = 1.905 \cdot HouseholdsWastewater \tag{6.1}$$

$$AWI_{dryseason} = 0.771 \cdot HouseholdsWastewater \tag{6.2}$$

Table 6.1: New or updated data for detailed 2030 scenario

Information	Value		Source
Precipitation in rainy season. Average[a]. (mm $month^{-1}$ / Mio. m^3 $month^{-1}$)	230 / 14.23	± 25%	1 / Eq.4.2
Precipitation in Dry Season 2011 (mm $month^{-1}$ / Mio. m^3 $month^{-1}$)	0 / 0	± 0%	1
Population in 2030 (Inhabitants)	463,113	± 3%	2
Groundwater flow (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	6.48 / 77.8	± 15%	3
Bottled Water flow (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.10 / 1.22	± 20%	4
Decentralised Water Supply flow (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.037 / 0.44	± 20%	4
Industrial Private Water Supply (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.43 / 5.17	± 20%	4
Industrial Direct Discharge flow (m^3 $month^{-1}$ / m^3 $year^{-1}$)	380 / 4,560	± 20%	4
NI/ND Private Water Supply (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.58 / 7	± 20%	4
NI/ND Direct Discharge (Mio. m^3 $month^{-1}$ / Mio. m^3 $year^{-1}$)	0.020 / 0.24	± 20%	4

[a] Corresponds to the historical precipitation for the months from June to October which is in total 920 mm.
NI/ND = Non-Industrial/Non-Domestic
Sources:
1-INEGI 2012
2-Consejo Nacional de Población 2012. This is equivalent to a population growth of 33%.
3-Calculated from the water consumption per capita obtained in the basic scenarios, service coverage and expected losses in 2030 as communicated by SIAPA Tepic.
4- Based on the amounts for 2011 plus an increase of 33% corresponding to the population growth expected between 2011 and 2030

6.2 Results and discussion

The results of the detailed 2030 scenario are presented in this section using the same indicators as in the detailed 2011 scenario. The results of the MFA for all flows and layers as obtained in STAN are included in Annex A for the rainy season and for the dry season. The discussion presented in this section focuses on the comparison of the situations in 2011 and 2030.

Since the official projections for population growth present a positive trend and the water consumption and pollution patterns were assumed to remain as in 2011, it is expected that by 2030 the water and N inputs to the city will increase. These increments are not discussed in this section. The discussion is rather focused in highlighting the differences between 2011 and 2030 in the flow ratios and in the performance indicators. The percentages mentioned in the discussion refer to differences in the flow ratios and not to the net increase or decrease of the flow. Differences smaller than 5% are not considered significant.

6.2.1 Sources and disposal routes

A comparison of the results of the 2011 and 2030 scenarios regarding sources and disposal routes of water and nitrogen is presented in figures 6.1 and 6.2. Regarding the water sources and disposal routes, only the overall increment in the total imports and exports is observable. The ratios of the different supply sources and disposal routes remain practically unaltered. The most concerning export flows are still the exports of raw sewage to the environment (sewage exports). According to the results, these flows will amount by 2030 to 3.5 Mio. m^3 $month^{-1}$ in the dry season (with expected high concentrations of pollutants) and 8.2 Mio. m^3 $month^{-1}$ in the rainy season (with expected low concentrations of pollutants) with an annual total of 60 Mio. m^3 of raw sewage being discharged to the environment.

Regarding nitrogen, the sources remain very similar as in 2011, but the disposal routes are altered to some extent. The exports through the Stormwater Sewer are decreased by 10% and the exports through the WWTP are increased by 5%. These improvements are explained by the reduction of the Sewer Export flow and by the increase of the wastewater treatment capacity at the WWTPs. The percentages refer to the rainy season. In the dry season, these improvements are also observed, but to a less extent.

However, even when the treatment capacity will increase by 2030, the total N input to the city will also increase and its increase will exceed the increase of the treatment capacity. Thus, the export of N in untreated sewage flows is expected to increase in the 2030 scenario by 5% compared to the detailed 2011 scenario. A total of 1,234 tonnes of untreated N is expected to be discharged to the environment during 2030 (in 2011 it was 900 tonnes of N).

Figure 6.3 presents the nitrogen exports according to its destination in the environment. It was observed that the changes in the export routes in scenario 2030 did not significantly affect the ratio of N discharged to surface water and to soil/groundwater. Those ratios will remain almost identical as in 2011.

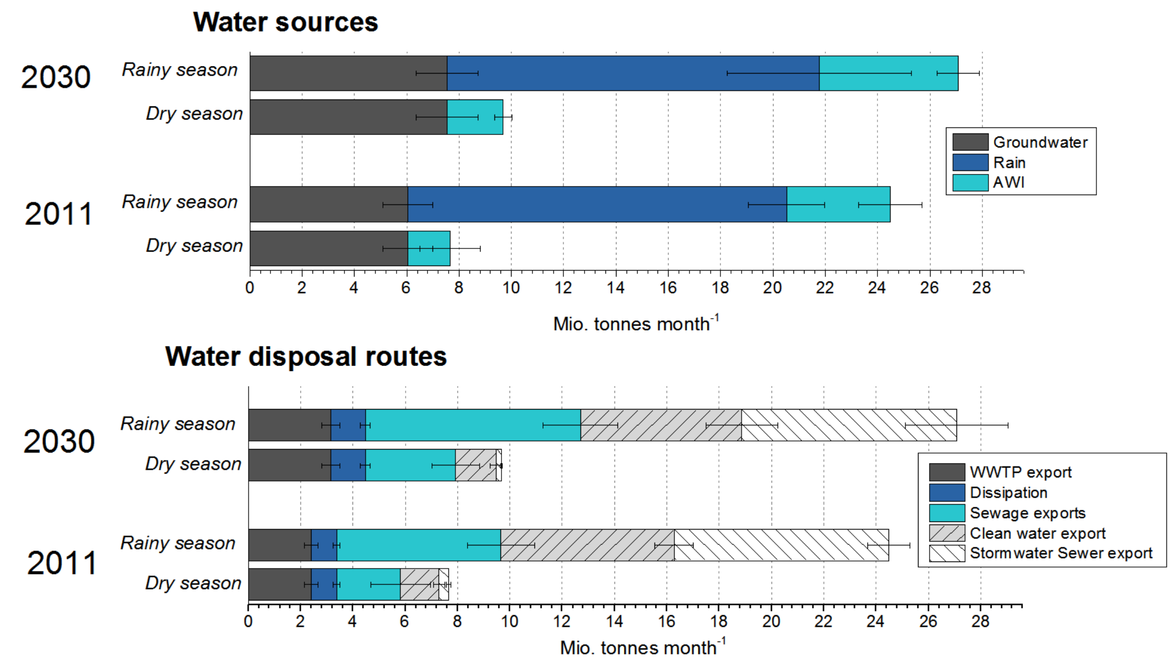

Figure 6.1: Monthly water balance in detailed 2030 scenario

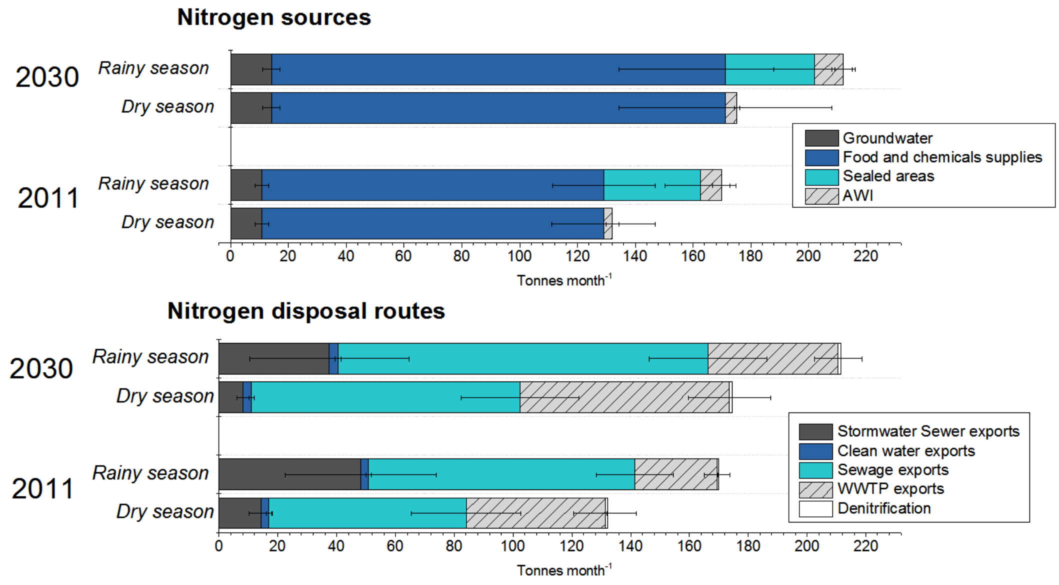

Figure 6.2: Monthly nitrogen balance in detailed 2030 scenario

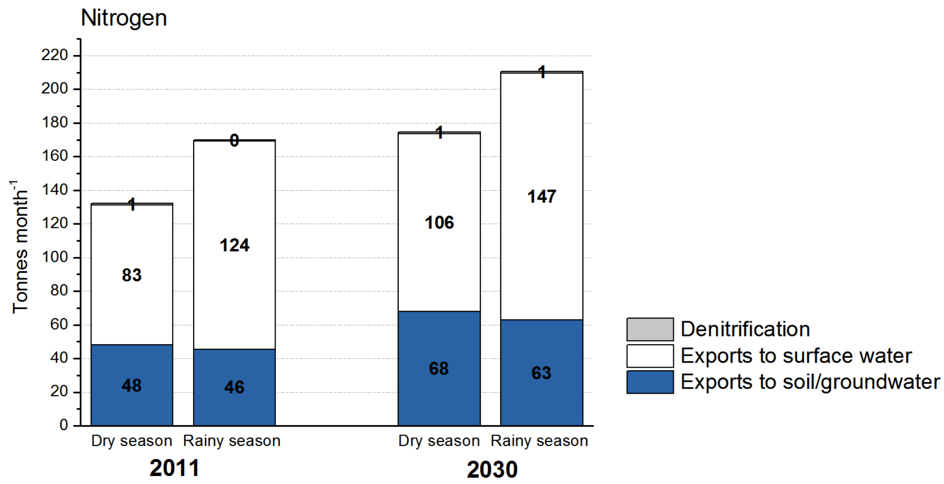

Figure 6.3: Monthly nitrogen outputs to the environment in detailed 2030 scenario.

6.2.2 Groundwater abstraction and recharge

In this chapter, the scope of the analysis was expanded to analyse the exhaustion of the groundwater generated by the city in 2030. The calculated groundwater abstraction by the public water works in 2030 is expected to amount to 77.8 Mio. m^3. Additionally, there is groundwater withdrawal from private users summing up a total groundwater input to the city of 90.4 Mio. m^3 $year^{-1}$.

The total aquifer recharge reported by official sources is 124 Mio. m^3 $year^{-1}$. From this recharge, 27 Mio. m^3 $year^{-1}$ are discharged naturally (water springs and horizontal discharge) and 16 Mio. m^3 $year^{-1}$ are committed to agricultural activities (CONAGUA 2009) leaving only 81 Mio. m^3 $year^{-1}$ for other kinds of activities. Consequently the city of Tepic alone will be using the totality of the available water by 2030. This will contribute to the depletion of the aquifer by 10 Mio. m^3 $year^{-1}$. The actual depletion rate and time does not only depend on the city of Tepic. There are many other settlements and agricultural activities in the region depending on the same aquifer. Thus, it is considered that the aquifer may present depletion conditions much earlier than 2030 or even already at the present.

6.2.3 Sewer performance

The total infiltration to the sewer in the detailed 2030 scenario is as follows: 7.45 Mio. m^3 $month^{-1}$ $\pm$ 18% in the rainy season and 2.54 Mio. m^3 $month^{-1}$ $\pm$ 15% in the dry season, totalling in 4.18 Mio. m^3 $month^{-1}$ $\pm$ 17% on average. Table 6.2 shows a comparison of the infiltration in years 2011 and 2030 using the indicators AI and IS previously described in Equations 4.7 and 5.7. It is observed that the infiltration indicators for the 2030 scenario are slightly lower than in 2011. This decrease can be attributed to the decrease in the rates of Permanent Infiltration and Seasonal Infiltration achieved by the improvement measures planned by the city. However, by having a look at the indicator IS it can be concluded that the improvements are not significant. The infiltration share remains practically the same in 2030 as in 2011.

Table 6.2: Infiltration in the detailed scenarios for 2011 and 2030

	Additions by infiltration		Infiltration share
2011			
average rainy season	191%	± 43%	65%
dry season	62%	± 37%	38%
average year	105%	± 39%	51%
2030			
average rainy season	176%	± 28%	64%
dry season	60%	± 10%	37%
average year	99%	± 18%	50%

The direct discharges of untreated wastewater and untreated N are also relevant indicators of the sewer performance. Figure 6.4 shows the amounts of wastewater and nitrogen in untreated flows for 2030 together with the amounts calculated for 2011. An overall increase is observed in both wastewater and N flows. The ratios observed for each flow in 2011 remain almost unchanged in 2030. Only the flow Sewer Export decreases slightly due to the reduction of interconnections and illegal discharges to the rain sewer. All other flows increased. By 2030 there is a total discharge of untreated wastewater of 3.6/8.5 Mio. m^3 $month^{-1}$ in the dry / rainy season. These monthly flows of wastewater contain 97/137 tonnes of untreated N (dry/rainy seasons).

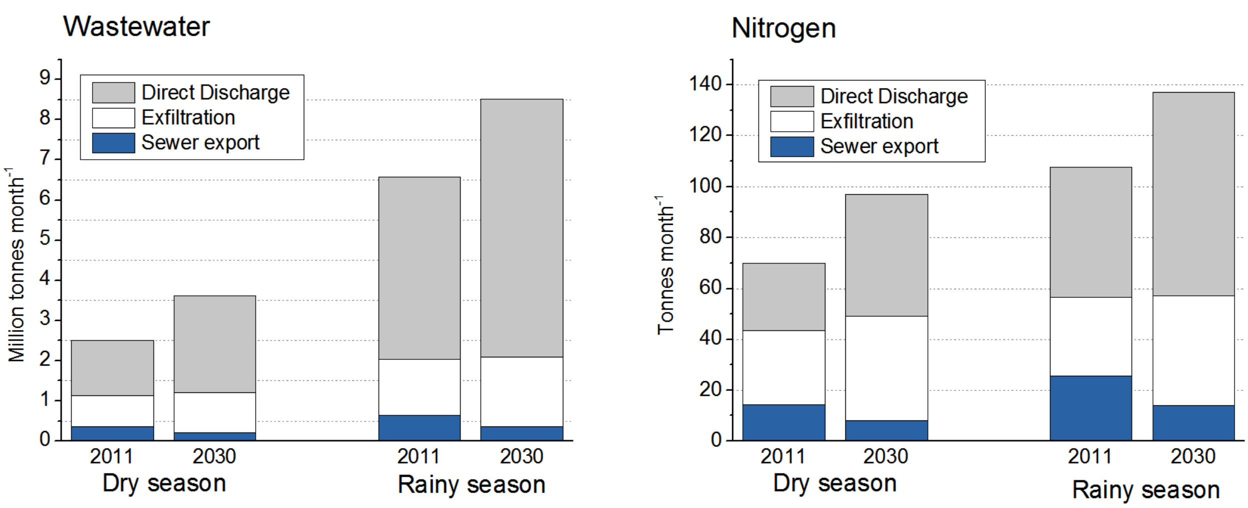

Figure 6.4: Water and nitrogen in untreated wastewater flows from detailed scenarios for 2011 and 2030.

The performance of the sewer can also be measured in terms of treatment coverage. Table 6.3 presents a comparison of the calculated treatment coverages for 2011 and 2030. It can be seen that the theoretical treatment coverage is not expected to change. This is because the treatment capacity will increase from 2011 until 2030 so that the increase in the wastewater generation is already considered in the planning. However, since the infiltrations persist in shares similar to 2011, the realistic treatment coverage remains almost unchanged at 47% during the dry season and at 27% during the rainy season.

Table 6.3: Comparison of the calculated treatment coverage in the detailed scenarios

	If infiltration = 0	**Considering calculated infiltrations:**	
		dry season	rainy season
Treatment coverage in detailed 2011 scenario	75%	46%	26%
Treatment coverage in detailed 2030 scenario	75%	47%	27%

6.2.4 Nitrogen in the export flows

Figure 6.5 presents the results for the N concentrations and N mass flows of all relevant export flows under rainy and dry conditions. The results of the detailed 2011 scenario are also included as a basis for comparison. It is shown that the N concentrations remain almost unchanged for all flows. As in 2011, there are also in 2030 numerous export flows which exceed the Mexican wastewater discharge limits for the protection of aquatic life (15 mg N L^{-1} as in NOM-001-SEMARNAT-1996) in rainy and dry seasons. The only significant difference is that the export flow Wastewater to Delicias was substituted by the export flow Discharge WWTP Delicias, given that this treatment plant will have started operations until 2030.

As a consequence of the population growth, the N input to the city will increase. This is reflected by the N exports which will also increase in 2030. Figure 6.5 shows an increase in the N mass flow of nearly all export flows in 2030 compared to the flows in 2011. The only decrease is observed for the flow Polluted Stormwater Sewer Discharge. The explanation for this is the decrement obtained in the Sewer Export flow by the reduction of the interconnections between WW Sewer and the Stormwater Sewer as well as the reduction of the illegal discharges to the Stormwater sewer. As it was the case in 2011, the N export trough untreated flows is larger in both seasons in 2030 than the N export trough treated flows. In the rainy season, 163 tonnes of untreated N will be exported per month versus 45 tonnes of treated N.In the dry season, the situation is expected to improve: 99 tonnes of untreated N will be exported per month versus 73 tonnes of treated N.

The term "critical flow" was used already in Section 5.3.4 to refer to flows exceeding the Mexican N discharge limits and/or representing 10% or more of the total N export (in terms of mass flow). A further criteria applied at this stage to identify critical flows was the N species (ammonia, nitrate) expected in the export flows: untreated flows are considered more critical than treated flows. Using these criteria, the following export flows were identified in 2030 as critical:

- Direct Discharge from WW Sewer
- Wastewater Exfiltration
- Polluted Stormwater Sewer Discharge (rainy season)
- Discharge WWTP Punto
- Sludge (all WWTPs)

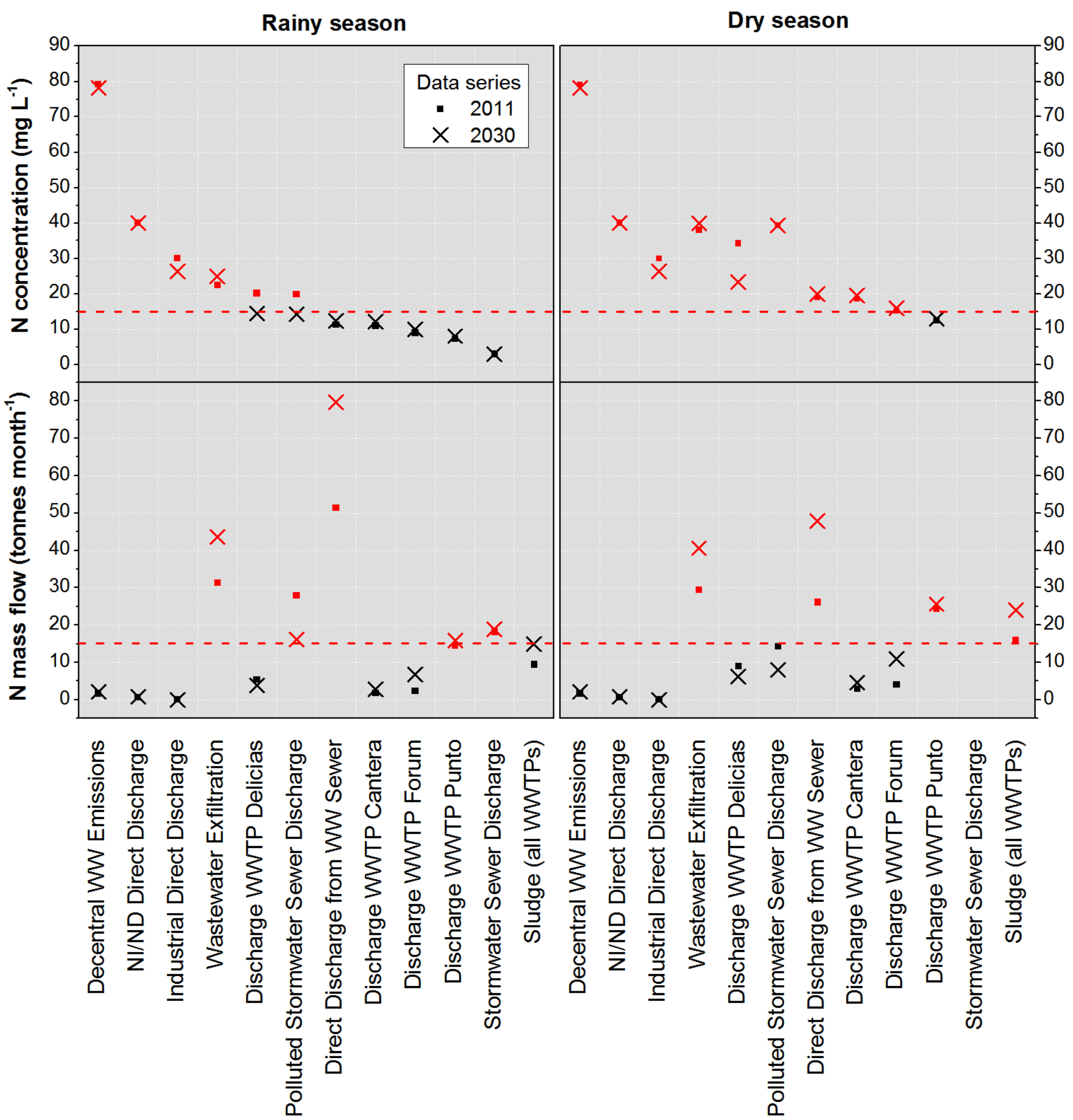

Figure 6.5: N concentrations and N mass flows in export flows in 2011 and 2030.
Upper graphs: the flows above the dotted line exceed the Mexican maximum limit for the protection of aquatic life.
Lower graphs: the flows above the dotted line represent more than 10% of the total N mass exports.

6.3 Conclusions

The detailed 2030 scenario for 2030 proved to have results very similar to those of the detailed scenario for 2011 regarding flow ratios and performance indicators. The improvements planned for the city in the period 2011-2030 seem to be insufficient to counteract the effects of a growing population on the WWMS of the city and on the environment. Therefore, the challenges in the future are similar to those existing currently.

Based on the analysis of the basic scenarios and of the detailed scenarios for 2011 and 2030, following challenging conditions have been identified as priorities to attend in order to decrease the negative impacts of the city on the aquifer and on the river:

- High water consumption.
- Large discharge of untreated wastewater to the environment.
- Large exports of nitrogen to surface water and soil/groundwater (in treated and untreated form).

6.4 Sensitivity analysis

To assess the impacts of parameter variations on relevant indicators, a sensitivity analysis was carried out. This analysis helps to identify which parameters are influencing most significantly the results and its uncertainty (Kenway et al. 2011). In other words, by means of a sensitivity analysis, key parameters for relevant evaluation criteria can be identified. The key parameters are those which affect the values of the selected criteria most.

The evaluation criteria selected for the sensitivity analysis were the challenges detected in the previous section, namely: water consumption (by the city, as total), untreated wastewater discharge, and nitrogen exports in treated and untreated form. The tested parameters were all input informations which have an influence on the calculation of the selected evaluation criteria. Each parameter was changed by +10% (one at a time) and the system was recalculated to evaluate the criteria and to calculate the impact of the parameter change. The basis for the sensitivity analysis was the detailed 2030 scenario and each parameter change was tested for both rainy and dry seasons. In the following sections the key parameters for each criterion are discussed. The detailed results of the sensitivity analysis can be found in Annex A.

6.4.1 Key parameters for total groundwater abstraction

The total groundwater abstraction of the city is obtained by adding the water supplied to Households, to Industrial and to NI/ND users as well as the water losses. The sensitivity analysis revealed that the water demand of the population, i.e. its domestic demand, plays a major role. It was irrelevant wheter the increase in the domestic demand was caused by an increase in the number of inhabitants or by an increase in the per capita water demand.

The second most important parameter is the water loss in the public water supply system followed by the water demand of the NI/ND users. The water demand of the industrial users has only a marginal effect on the total groundwater abstraction of the city. There was no difference in the total groundwater abstraction in rainy and dry seasons.

These results indicate that in case of efforts to be done for reduction of the total groundwater abstraction, the most important target group should be the Households followed by efforts to decrease water losses from the system.

It can be argued that the water losses themselves do not represent a threat to the aquifer, because they finally infiltrate the soil and are thus recharged to the aquifer. Nevertheless, the costs induced by unnecessary pumping of water cannot be ignored as well as the fact that some of the lost water will infiltrate the WW Sewer and will thus unnecessarily increase the volume of wastewater requiring treatment before discharge.

6.4.2 Key parameters for discharge of untreated wastewater

The total discharge of untreated wastewater is calculated by adding all direct and diffuse sewage discharge flows to the environment including the export of wastewater from the WW Sewer to the Stormwater Sewer. Regarding this evaluation criterion, it was found that the extent of the water utilisation of the domestic users and NI/ND Users plays the most important role. According to the information used in this research, the utilisation ratio of the water inputs in Households and NI/ND Users is 75%, meaning that 25% of the water is dissipated and does not enter the WW Sewer. This utilisation ratio defined the TC of the inputs into the outputs at each of these processes in the model. If this utilisation ratio increases also the wastewater generation is increased and as a consequence, the discharge of untreated wastewater increases as well.

Other parameters showing a relatively high sensitivity are the population number and the total infiltration to the WW Sewer. The increase in water consumption of the NI/ND Users and of the industry and the increase in the water losses also augments the total discharge of untreated wastewater, but this increment is much less significant.

On the other hand, a positive effect is observed when the capacity of the WWTPs is increased, namely when the discharge of untreated wastewater is reduced. However, this evaluation criterion is more sensitive to changes in water utilisation ratio, population number and total infiltration.

Therefore, to reduce the untreated wastewater discharges, the efforts should be focused on the reduction of wastewater generation by Households and on the reduction of infiltration to the WW Sewer, followed by an increase in treatment capacity of the WWTPs.

The above mentioned key parameters and statements are valid for both dry and rainy seasons although the sensitivity in each season can differ. For example, an increase of the population increases the discharge of untreated wastewater in both dry and rainy season. However, the net increase is less during the dry season (see details in Annex A).

6.4.3 Key parameters for nitrogen exports to the environment

The nitrogen exports to the environment take place through untreated and treated flows. For the export of untreated nitrogen, especially three parameters are sensitive: the population number, the N load per capita in Households and the utilisation ratio of the water at Households and NI/ND Users. The total infiltration, the N input of NI/ND Users and their water consumption as well as the input of N from the sealed areas during the rainy season are slightly sensitive factors but do not affect the export of untreated N to a large extent. The increase of the treatment capacity of the WWTPs of course generates a decrease of the untreated N exports.

Regarding the export of nitrogen in treated form, the treatment capacity of the WWTPs is the most sensitive parameter followed by the per capita N load in Households and the N input from the NI/ND Users to a small extent. All other parameters are not sensitive. Two factors were found the increments of which negatively affect the exports of treated N: total infiltration as well as water utilisation ratio. When these parameters increase, the exports of treated N decrease.

The above mentioned key parameters and statements are valid for both dry and rainy seasons although the specific sensitivity in each season can differ. Details are found in Annex A.

Chapter 7

Improvement needs and options

7.1 Water consumption: control and decrease

The high water consumption in Tepic is one of the most challenging conditions for the WWMS. It does not only results in depletion of the aquifer, but also generates large quantities of wastewater. The sensitivity analysis (Section 6.4) revealed that the population number plays the most important role in the system in terms of groundwater abstraction. The key influencing parameters are the population number and the per capita water consumption.

Influencing the population number of a city requires a socio-political approach which is not within the scope of this thesis. Thus, the focus of this discussion is centred on measures to control and decrease the per capita water consumption. This can be achieved by means of improvements in water use efficiency introduced by behaviour changes or by technical improvements.

The average per capita consumption calculated in this study for Households in Tepic is around 250 L inh^{-1} day^{-1}. This calculation was based on the knowledge of the population number and on information provided by the SIAPA regarding annual water abstraction volumes, water losses, users distribution and service coverage (Annex A and section 4.4). This approach was taken because of the low rate of consumption measurement in Tepic. The latest national report about the urban water systems states that only 6% of the domestic water intakes and 14% of commercial intakes in Tepic are quantified by means of micromeasurement devices. However, the actual measurement rate is 1.6% of the domestic intakes and 7% of the commercial ones. The remaining devices are out of order (CONAGUA 2014). To obtain accurate information about the water consumption and expected wastewater generation, it is essential to install volume measurement devices at Households, NI/ND Users and Industry and that they are actually properly operating. This ensures also more control and transparency in the billing process and it helps to generate better consumption forecasts for the future. Additionally, a billing process based on the actually consumed volume may positively influence consumers and motivate them to lower their water demand in order to pay less water fees.

According to the World Health Organisation (WHO), a person needs 50 to 100 L per day to meet basic needs including drinking, sanitation, personal and household hygiene (United Nations 2011). In Germany, where the population is expected to have a higher average living standard than in Mexico, the per capita water consumption at households is 121 L inh^{-1} day^{-1} (state 2010. Statistisches Bundesamt 2013). The United States (USA) are one of the countries with the largest per capita water withdrawal in the world (World Business Council for Sustainable Development 2005). The average domestic water consumption in USA is 333 L inh^{-1} day^{-1} (88 gal inhabitant day^{-1}). The consumption ranges from 193 to 636 L inh^{-1} day^{-1}(51 to 168 gal inhabitant day^{-1}) being larger in the Mountain and Western States where the outdoor use of water is more intense due to gardening, pools, ponds and other landscape features (state 2010. Maupin et al. 2014).

In Tepic, less than 3% of the users registered by the SIAPA belong to a high socio-economic category and could be in conditions of having such a luxurious life as in the Mountain and Western States of USA with large gardens and pools (Castillo Delgado 2007). According to the observations made on site, the high water consumption in Tepic probably originates more from an inefficient use of the water rather than from actual large water needs.

According to Tchobanoglous et al. (2003), the largest amount of interior water use in households is used for the purpose of toilet flushing, followed by clothes washing and showering. The use of the faucet for miscellaneous activities (hands washing, tooth brushing, etc.) also represents an important water use. The research of Martinez et al. (2011) shows similar results: in the Mexican city of San Luis Potosí, 15% of the total domestic water use takes place in the kitchen, 30% in the shower, 35% is used for the toilets and 20% is used for laundry purposes.

A comparison of water consumption with and without water conservation practices and devices in USA and in Germany revealed that it is possible to achieve a 30% reduction of the total water consumption when better practices and technologies are applied. The largest improvement potential was found in toilets and in reduction of internal water losses (leaks). Improved practices for clothes washing and showering also results in important savings. Table 7.1 shows the details for these calculations.

Observations made during the research on domestic water use in Tepic show that only very few homes in the city dispose of a bathtub and that dish washing

Table 7.1: Comparison of domestic water consumption in USA and Germany with and without water saving practices

Use	Flow (L inh^{-1} day^{-1})				Possible savings (%)	
	without saving		with saving			
	USA	GER	USA	GER	USA	GER
Personal hygiene[a]	55	46	47	39	8%	15%
Dish washing	4	8	4	10	0%	0%
Clothes washing	64	15	45	12	30%	20%
Faucets	43	n.d.	42	n.d.	2%	n.d.
Toilets	73	35	35	20	52%	43%
Leaks	36	n.d.	18	n.d.	50%	n.d.
Other domestic use[b]	6	13	6	9	0%	30%
Total	*281*	*128*	*197*	*90*	*30%*	*30%*

[a]Personal hygiene includes showering, bathing and other personal cleaning activities. [b]Other domestic use includes house cleaning, cooking and drinking. In the case of Germany it also includes water used in the garden and for car washing.
Data for households in USA based on Tchobanoglous et al. (2003).
Data for households in Germany based on Lange et al. (2000)

is mostly done by hand under a tap and not by automatic dish-washing machines. Thus, the investigated technical and infrastructural alternatives for Tepic focus on improved toilets, taps and showers.

An extensive research was conducted in the framework of this thesis about low-cost wastewater collection technologies (Velarde Raudales 2011) and about best management practices for drinking water (Lafratta 2014). Based on this research, two main categories are recognized to reduce the water demand at homes: (1) technical and infrastructural changes and (2) cultural and behavioural changes.

The motivation of the population to implement technical improvements in households or to introduce better practices can be driven externally or internally. External motivation is given for example if during the construction of houses in new dwellings only flow-reduction devices are allowed or when the number of appliances using water is restricted (Tchobanoglous et al. 2003). Another example of external motivation are financial incentives: when water fees per cubic meter are high or when they increase after a certain basic volume has been consumed, there is an incentive to use the water more efficiently and reduce consumption (Lange et al. 2000). On the other hand, there is also the possibility of internal motivation. This is given when the individuals are truly concerned about water conservation and pollution issues. This is achieved by cultural and behavioural changes.

A summary of the studied alternatives to decrease the water consumption is provided below based on the research works of Velarde Raudales (2011) and Lafratta (2014). A more detailed discussion about the alternatives including costing information and more detailed bibliographic references can be found in the separate reports. The discussion in this thesis focuses on the impacts of reducing the water consumption.

7.1.1 Alternatives for reducing water consumption

Water saving in toilets. Very old toilets require up to 15-23 L per flush. A modern water saving toilet requires 6-13 L per flush (Tchobanoglous et al. 2003). According to the DWA (2008), a conventional toilet requires nowadays 9 L per flush. As a person utilises the toilet several times per day, the water saving potential of toilettes is very large. There is a wide range of alternatives to decrease the water requirements of toilettes. The simplest one is an improved version of the conventional toilet, the design of which allows a proper flush and discharge of the excreta with less volume of water. Other versions are more flexible and have with two buttons allowing a minor discharge (3 - 4 L) or a larger discharge (6 - 9 L) from a unique toilet tank according to different needs. There are models which have a stop button instead, allowing the user to decide when the water flow should cease. The combined use of urinals and toilets also results in water savings. A traditional urinal requires only about 3 L per flush (Ilesanmi 2006, DWA 2008, WATACLIC Partnership 2011)

Dry urinals do not require water for their functioning at all, although they might require water for cleaning purposes. The so-called separating toilets work under a similar principle. They count with two separated zones in the toilet bowl. The front zone receives only urine and does not necessarily require flushing. The rear zone collects faeces and requires flushing with water just as a normal (improved) toilet. Vacuum toilets are also existent in the market and they are mostly used in trains, ships and aircraft. They can operate with less than 1.5 L per flush. However, their application requires more fittings than a normal toilet. Additionally a pumping station is required. This increases the investment and operation costs and reduces its practicability at homes (WATACLIC Partnership 2011). A modern and more sustainable version of the vacuum toilet includes biogas reactors into the concept. An example of this is found in the project "KREIS" for energy recovery and waste water management in Germany. There, the black water (faeces, urine and flush water) is collected via vacuum toilets and it is then digested anaerobically together with organic waste to generate biogas. A demonstration dwelling is found in Jenfelder Au (Hamburg, Germany) (Bauhaus-Universität Weimar 2015).

Further options are dry toilets. These are existent in low-tech and high-tech versions. Low-tech versions of dry toilets are commonly known as pit-latrines or composting toilets. Good examples of such can be found in the project "Resource-Oriented Sanitation concepts for peri-urban areas in Africa" (ROSA) which promoted resource-oriented sanitation concepts and included the use of different dry toilets in the researched alternatives (University of Natural Resources and Applied Life Sciences Vienna 2015).

The connection of homes to the sewer system in Tepic is very high (98%), this makes the conversion of toilets from centralised to decentralized alternatives very difficult and costly. Besides, the users may not be willing to adapt to a different system. The application of water saving toilets and the adjustment of conventional toilets to water saving schemes is considered as the most feasible and realistic option in the short and middle term for the city of Tepic. However, in the course of new dwellings developments or in the case of selected locations, decentralized options with low or no water requirements can be integrated to reduce the overall water demand and ambitious projects might be realised as the users develop a more conscious attitude towards water consumption.

Water savings in taps and showers. There are three main possibilities for reducing the water consumption in operations such as washing dishes, teeth brushing, hands washing and showering there are three main possibilities. The first one is to install flow control valves to the taps or shower heads. The objective is to increase the flow pressure and limit the maximum water flow so that less water is required for the same activities. A second option is to install mechanical or automatic flow controls replacing the traditional knobs. In this case the water flow is only activated when the mechanical control is pressed or when a sensor detects an object front of it. The water flow is switched on for a pre-determined period of time and stops automatically. These devices are commonly used in public bathrooms for hygienic purposes. With automatic devices, the users do not have to touch the tap, and thus the dissemination of pathogens is avoided. A third option is the use of monobloc mixer tabs. Instead of having two knobs one for cold water and one for hot water, a monobloc mixer gives the user the possibility to mix hot and cold water with a unique knob, finding the right temperature of water easily and faster and thus saving water. With the above mentioned fittings, a water reduction of 30-50% can be achieved. Up to 70% can be saved with automatic flow controls, provided that the users also have a water saving behaviour (WATACLIC Partnership 2011).

Reducing water losses. Water losses in pipelines and water leaks at homes are common problems unlikely to be eradicated. However, it is important to establish a management strategy for water loss control and to keep the loss rates as low as possible (Lafratta 2014). Well-managed systems often have less than 10% of losses. Poorly maintained systems can have 50% or more. One factor influencing the water losses, is the water pressure in the pipelines. This can be regulated for example by means of flow control valves or pressure-balanced valves at strategic locations of the drinking water network or of the house piping.

Furthermore, it is necessary to repair damaged pipes and damaged fittings to avoid unnecessary water losses. Water losses can also take place by careless behaviour when the water taps are not closed properly or when it is forgotten to close them after use (Maddaus et al. 2013)

Introducing cultural and behavioural changes. The research about low-cost (and low water consumption) toilets (Velarde Raudales 2011) demonstrates that all appliances require at least a minimum of operation and maintenance skills. Lafratta (2014) emphasizes that appropriate behaviour is necessary to obtain the maximum benefits of any water saving device. Numerous publications of governmental and Non-Governmental Organizations (NGOs) agree that positive cultural and behavioural changes are required amongst the population in order to increase water use efficiency (e.g. Maddaus et al. 2013, PADCO 2001) and for the greater goal of integrated resources management (Hülsmann et al. Hülsmann et al.). There are plenty of improved behaviours leading to a reduction in water consumption and to the prevention of water pollution with or without need of additional fittings. For example, closing the water tap while brushing teeth or washing hands, watering the gardens at night instead of during the day, and a correct dosage of laundry detergents (Lange et al. Lange et al.). However, a main concern is how to motivate the individuals to change their attitude and water consumption habits.

There are several ways to motivate the consumers to improve their attitude towards the use of water. The realisation of campaigns for rising environmental awareness is one of them. Such campaigns usually focus on spreading information about how important it is to use the water efficiently and on how can efficiency be achieved. Awareness campaigns commonly use marketing strategies to make the messages more attractive. The target is the population in general, but the campaigns can also target businesses. They can make use for example of print and electronic media, social networks and events to get their message across a wide audience. Good examples of campaigns are the "Use Only What You Need" campaign in Denver or the "Beat the Peak" campaign in Cary, North Carolina, and Tucson, Arizona (USA). Another way of fostering a conscious attitude towards water is to let the public get involved in the local or national water conservation plans. This is called public participation. Public hearings and open communication channels give customers and interested persons the chance to review and comment on the proposed objectives and measures. It also gives the chance to modify or customize the water use plan according to the interests and concerns of the users. This encourages the acceptance of the proposed measures and it builds more interest about the topic (Maddaus et al. 2013).

The use of quality labels for products or services which make use of water is another way of motivating a more efficient behaviour. A quality label is an award assigned to companies or products that achieve specific objectives of water efficiency. The costumers then can take these labels into consideration while selecting a product of service and save water while using them. For example, the "WaterSense" program of the USA Environmental Protection Agency (USEPA) introduced a quality label in the country to encourage people to save water by choosing WaterSense labeled products. According to their own statements "Products and services that have earned the WaterSense label have been certified to be at least 20 percent more efficient without sacrificing performance" (WaterSense 2015). Further examples of successful quality labels are the Water Efficiency Labelling and Standards in Australia (WELS Australia) and the voluntary Water Efficiency Labelling Scheme in Hong Kong (WELS Hong Kong). In the European Union, the European Water Label has a similar scheme as that of the energy labels currently on use for electric devices and its importance is growing.

To motivate an efficient use of the water, changes in the water tariff pricing can also be of use. In Mexico, the conventional water tariff system is based on a fixed payment according to the user classification as in the case of Tepic or in metered water use charges where measurement devices at home are in operation. The introduction of a metered service where no volume measurement is on place or the use of inclining tariffs charging more per unit as water use increases can be theoretically positive for promoting water conservation. This is a challenging procedure which can also provide for more fair payment and revenue assurance for the water operating company (Maddaus et al. 2013). However, it can also face opposition from the customers for what they consider an increase in their costs and the procedure may also fail when the political support is not given. The vicious cycle in water and wastewater systems (Figure 7.1) demonstrates the correlation.

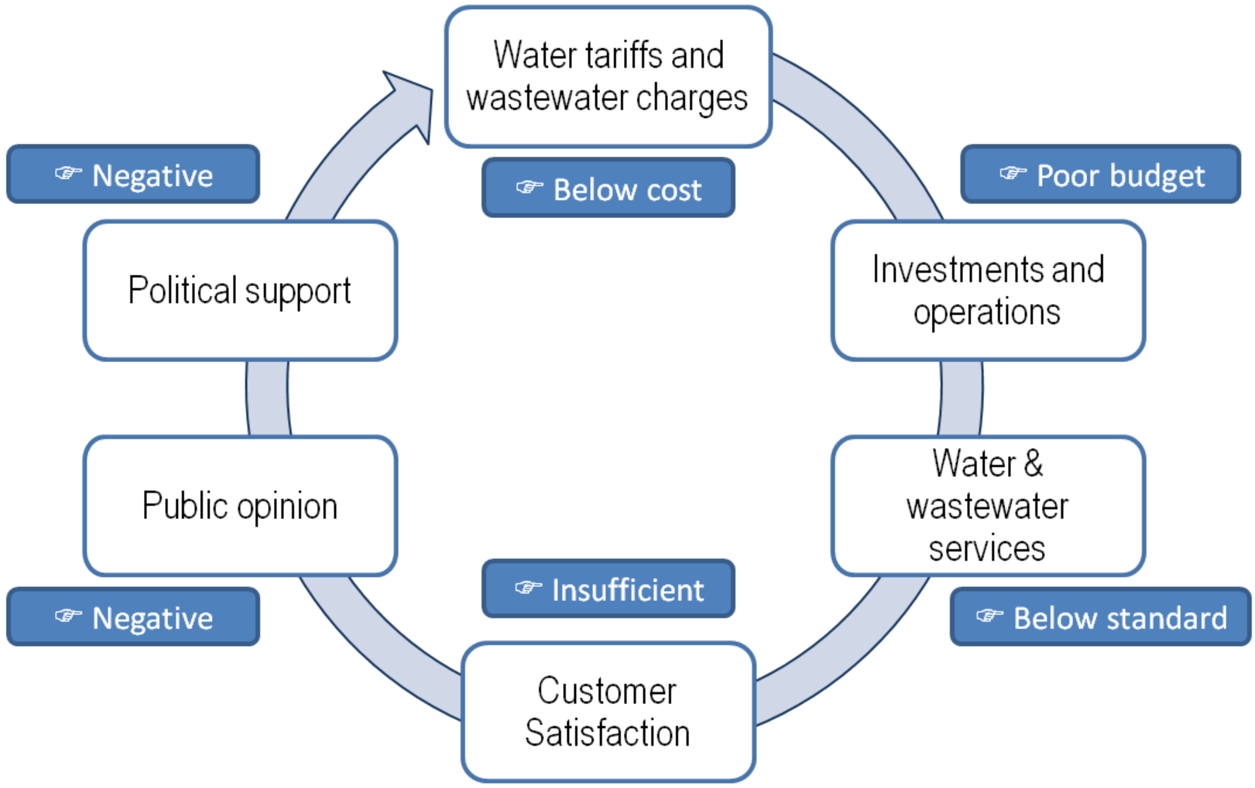

Figure 7.1: The vicious cycle in water and wastewater services
(based on Rudolph 2009 as presented by Maddaus et al. 2013)

7.1.2 Impacts of reducing water consumption

To assess the potential impacts of reducing the water consumption at homes and NI/ND users, several scenarios were created simulating the reduction in consumption. Additionally, it was simulated that the water losses in the drinking water network (process Water Supply) would be reduced. All simulations took the detailed scenario 2030 as basis for the modifications. The N load from the polluting processes was left unchanged in the simulations so that the N concentration in the generated wastewater increases parallel to the reductions in the water consumption due to the volume reduction.

The reviewed literature indicates that a 30% reduction of domestic water demand is a feasible goal. However, by comparing the current water demand of 250 L inh^{-1} day^{-1} with the average demand of several industrialized countries (EUROSTAT 2015) it was considered that a 50% reduction to about 125 L inh^{-1} day^{-1} could be an ambitious yet feasible objective. Figure 7.2 shows a summary with the results of the simulations for 10% to 50% reduction of water demand and of water losses in the supply system.

The results of the simulated scenarios indicate that a 10% reduction would allow to reduce the total water imports to the city just to a level equal to the aquifer recharge. A 20% reduction and above would give room for demand expansion. Otherwise, the city risks the depletion of the aquifer.

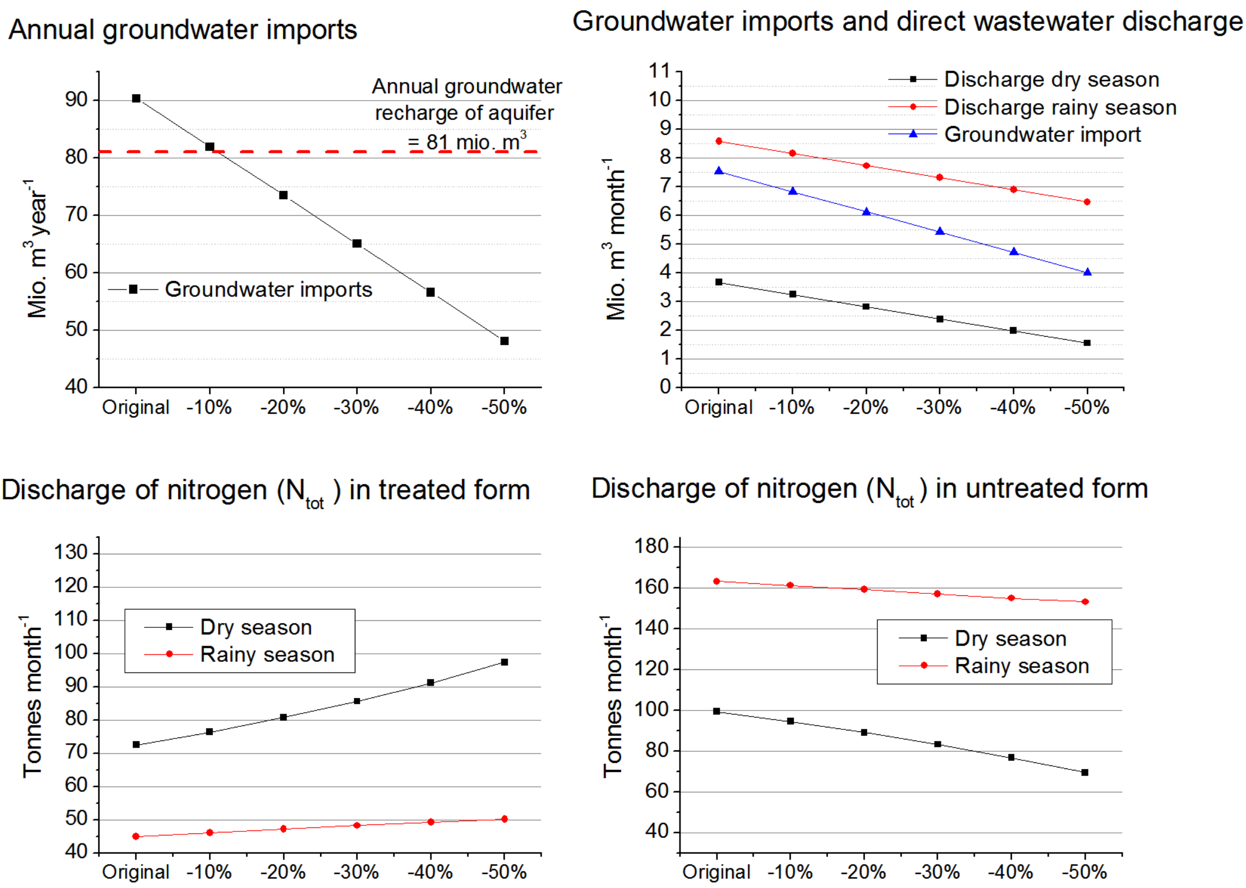

Figure 7.2: Impacts of reducing water demand in the city.
The diagrams show the impacts of reducing the water consumption at Households and NI/ND Users and of reducing the water losses in the pipelines. The X axis shows the simulated percentages of reduction. Aquifer recharge as stated in CONAGUA 2009.

The discharge of untreated wastewater to the environment is reduced when the water consumption decreases because less wastewater is produced. The treatment coverage increases correspondingly. In both dry and rainy seasons, the efforts invested in the demand decrease are valuable. For each reduction of 10% in the water consumption, the direct wastewater discharges are reduced by 11.5% in the dry months and by 5% in the rainy months. There is a difference between the seasons because in the rainy months, the I/I to the sewer is much larger than the actual wastewater generation and thus, a reduction in the wastewater generation has a lower impact on the total discharges in these months. In absolute figures the reduction of the wastewater discharges is as follows: for each m^3 of drinking water that is saved on the consumption side, 0.6 m^3 of direct wastewater discharges are avoided (ratio of 1:0.6)

Furthermore, as the water demand decreases, the discharge of N in treated form increases and the discharge of N in untreated form decreases. The effect is more pronounced in the dry season, given that the wastewater has higher concentrations. The reduction of untreated N discharges has a positive effect on the river water quality since the discharge of the most toxic N species is reduced. Nevertheless, considering that the total N imports to the city remain unchanged, the N concentration in the export flows increases along with the water consumption reduction. This is especially critical in the dry season. Literature data indicate, that the growth rate of the activated sludge microorganisms as well as the biological pollutant removal rate is reduced, when the nutrient concentration in the wastewater entering a biological treatment plant is low (Decker 1998, Renner 2006). Thus, higher concentrations of nutrients in the influent of a WWTP could have a positive effect on the treatment efficiency because the biodegradation rates are improved. However, the extent to which the WWPTs in Tepic will be able to cope with increasing pollutant concentrations is uncertain. This fact emphasizes the importance of including nutrient removal and recovery schemes at the WWTPs and of integrated water management plans.

The scenarios for water demand reduction teach us, that the improvement in the water use efficiency bring benefits along with new challenges. When the water demand is decreasing, also the abstraction costs will decrease, the aquifer is preserved and the wastewater discharges to the river also decrease, especially those of concern which are the non-treated ones. However, the increase in the N concentration of the flows would eventually require adjustments in the wastewater treatment facilities. An excessive flow reduction may also result in pipe clogging due to the loss of traction in the sewer pipelines (Hennerkes 2006).

Besides reducing the water demand by means of improved appliances and improved practices, the water demand of homes (and cities) can be reduced through the collection and use of rain water and through the reuse of wastewater. By means of sustainable stormwater management, the aquifer recharge can be enhanced. Section 7.3 deals with improvements in the stormwater water management of the city of Tepic and Section 7.4 deals with the aspects of wastewater reuse.

7.2 Infiltration and exfiltration: assessment and decrease

A large infiltration to the sewer in Tepic was detected by means of the detailed scenario 2030. During the rainy season, the Additions by Infiltration (AI, see definition in section 4.3.4) are in average 60% and during the rainy season 176%. The exfiltration rate estimated by the operators of the WWMS is about 15% of total sewer inputs and it will represent an average export of 42 tonnes N_{tot} month^{-1} to the soil and groundwater by 2030.

A first successful approach for the experimental assessment of the infiltration in Tepic was carried out in collaboration with the local water operators (SIAPA Tepic) and the university (UAN-ACBI) (Espinosa Gutiérrez et al. 2015). This study provided experimental evidence for a high infiltration rate in the city. The calculated infiltration presents a large variability depending on the location and time of the measurements. However, the AI in most of the locations was above 50%. In some locations even up to 500% AI was calculated. More detailed studies are considered necessary in order to assess the I/I and the exfiltration rate in the city. The measurements should make the most out of the existent infrastructure and capabilities to provide for a prompt and reliable experimental measurement.

7.2.1 Sources and implications of infiltrations and exfiltrations

The exfiltration takes place when the pipelines of the sewer network are damaged and hydraulically overloaded. The internal water pressure forces the sewerage into the surrounding grounds (Read and Vickridge 1997). When the internal pressure drops, water from the surroundings (groundwater, drinking water) can enter the sewer through cracks of pipes or faulty connections (Infiltration). Water can also enter the sewer during or after rain events for example through roof or yard drain connections, through uncapped cleanouts, or faulty manholes (Direct Inflow). The infiltration induced by sump pumps, foundations drains, and rainfall is known as Delayed Inflow (EPA 2014). After heavy rain events, the Delayed Inflow may last up to 10-20 days (Fischer 1991). The above described undesired inputs of water to the wastewater sewers are generally known together as Infiltration and Inflow (I/I). In the case of separated sewer systems, rain is always considered as an undesirable inflow to the wastewater sewer. In the case of mixed sewer systems, the rain is considered in the planning and dimensioning of the system and therefore, it is not considered as part of the I/I.

Infiltration and exfiltration are two closely related processes. Both can happen at the same location or pipeline section depending on the level of the water table and on the hydraulic head inside the pipeline (Figure 7.3). Figure 7.4 shows possible entry points of I/I.

The impacts of I/I on the WWMS are diverse. Due to the increase in volume, the I/I affects the amount and pollutant concentrations of the water in the sewer. Depending on the origin of the infiltration, the entry of additional pollutants to the sewer is also possible. This has negative impacts on the efficiency of the system and on the operation costs which tend to increase with increasing I/I (Decker 1998). When the I/I is too large, the regulation tanks at the WWTPs need to be expanded to cope with the additional volumes. There is also the risk of over-flooding of the sewer system and Combined Sewer Overflow (CSO) increases or it occurs more often. Additionally, the WWTPs commonly present lower pollutant removal efficiencies when influent volume flows are increased (Renner 1996, Decker 1998, Ernst 2003, Hennerkes 2006, Bertrand-Krajewski et al. 2006). There is also the risk of an increased discharge of untreated pollutants to the environment (Espinosa Gutiérrez and Otterpohl 2014). The exfiltrations represent a direct potential risk of pollution of the soil and the aquifer (Huang

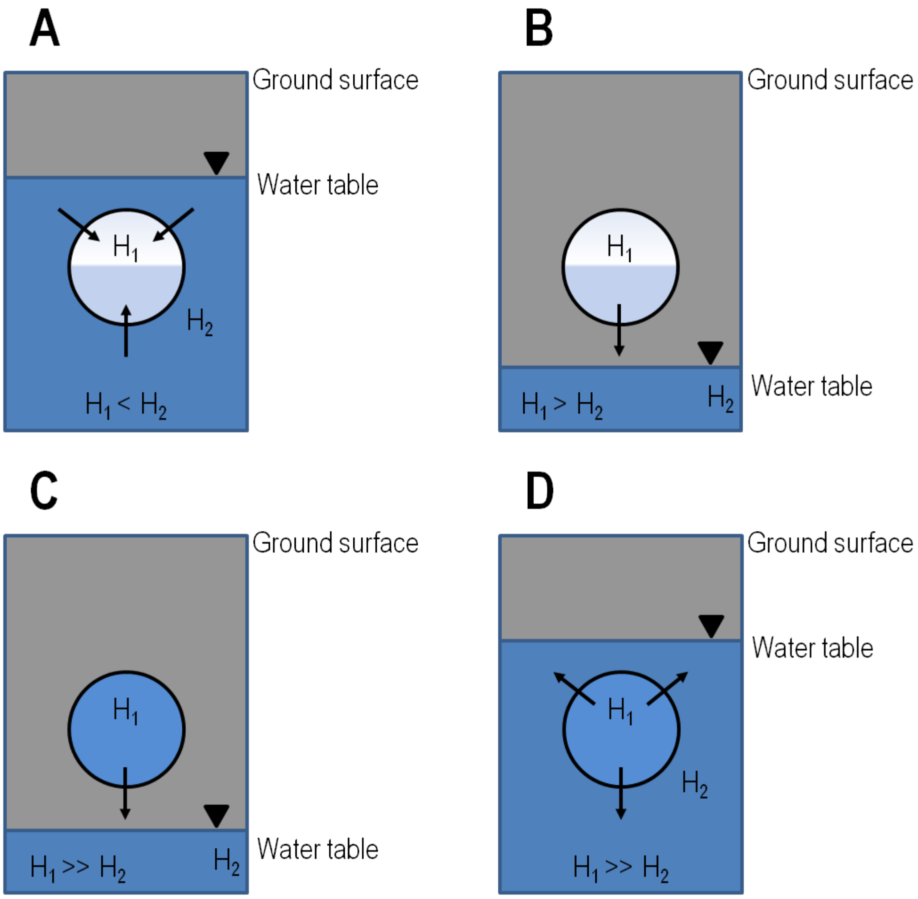

Figure 7.3: Cross sections of a sewer pipeline showing possible locations relative to the water table and the prevailing flow direction of water through cracks.
A: gravity drain sewer below water table; B: gravity-drain sewer above water table; C: force main above water table; D: force main below water table. H1 and H2 represent hydraulic head inside and outside the sewer respectively. Arrows show directions of potential sewer leakage.
Source: based on EPA 2014

et al. 2007) with a negative impact on the health of the population dependent on such an aquifer. The negative impacts of the I/I on the sewer system and on the efficiency of the WWTPs are more significant than those of exfiltration (Ellis 2001, Ellis 2010). For this reason, its measurement is more common or even routine (in some countries it is legally required) than the measurement of exfiltration. The I/I has been studied for longer time than exfiltration. For this reason the measurement methods for I/I are also more diversified and used (Benedittis and Bertrand-Krajewski 2005).

The I/I and the exfiltration affect also the WWMS by accelerating dereliction of the sewer network. Together they trigger the rupture and collapse of the sewer pipes because the stability of the grounds around the pipes is reduced due to the movement of water and soil around the pipes and to the creation of voids (Benedittis 2004). When the I/I and the exfiltration are extreme and the sewer collapses, it has negative effects on the overall local economy due to the environmental, infrastructural and social damages (Read and Vickridge 1997).

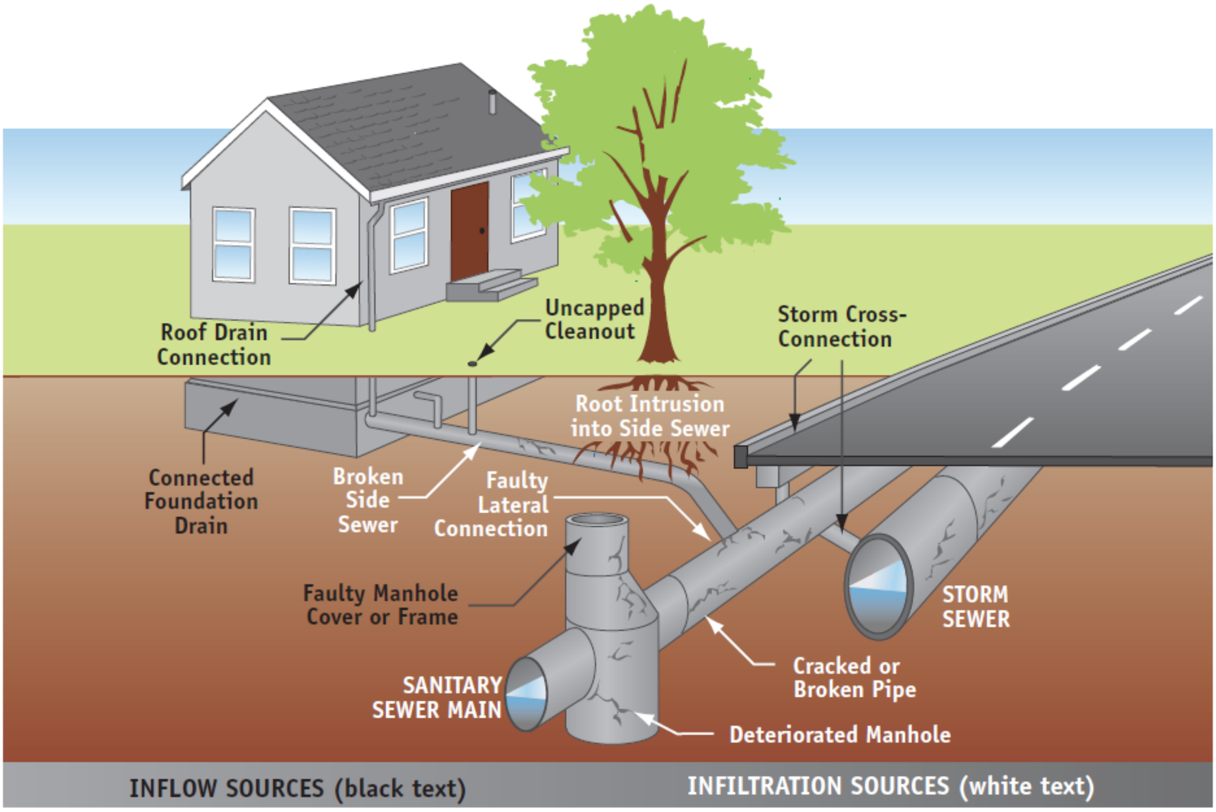

Figure 7.4: Sources of Infiltration and Inflow in sewer systems. Source: King County 2011

Some authors believe that I/I needs to be eliminated completely from the system either for cost-to-treatment reasons or for environmental reasons. Health and safety issues play also a role, since I/I can generate a reduction of the conveyance capacity of the sewer and produce CSO sooner than expected. Small sources of I/I are probably not really significant for the performance of the WWMS, and it may cost more to eliminate them than to treat them. However, large sources of I/I, the influence of which is noticed at the head of the WWTPs, should be removed (Day 2000). Infiltration can also have positive effects on the sewer system. Due to the increased flow in the pipes, the transportation of suspended or solid materials is improved and sediment formation and fouling is prevented. Through the input of oxygen from rain water, the anaerobic decomposition of the wastewater components is reduced and odours are minimized. Furthermore, the infiltration of groundwater to the sewer pipelines may help to reduce the groundwater levels and thus it may prevent swamps or flooding (Frechen and Köster 2003, Hennerkes 2006). Despite these advantages of I/I there is consensus among specialists that I/I should at least be assessed and it should be either minimized or accounted for in the system. Ignoring I/I may lead to unexpected failures on the sewer system and wasting of financial resources. Besides, exfiltration should be minimized as far as possible to avoid pollution of the groundwater and health problems among the population.

7.2.2 Assessing infiltration and exfiltration: an approach for Tepic

The work in this thesis does not aim at presenting a detailed comparative study of the available methods, but on suggesting a specific approach for the city of Tepic based on the local frame conditions and most pressing needs. Details about the different methods and their relative advantages and drawbacks are found in Benedittis (2004), Benedittis and Bertrand-Krajewski (2005), Mitchell et al. (2007) and in LUBW (2007). Additionally, the European project "Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems (APUSS)" developed innovative methods and tools to assess infiltration and exfiltration rates from urban sewer systems. A database with numerous documents about the newly developed approaches is found under http://apuss.insa-lyon.fr or in Ellis and Bertrand-Krajewski (2010).

The methods for the measurement of infiltration and exfiltration can be allocated to one of two categories: (1) methods based on volumetric measurements and (2) methods based on the measurements of pollutants concentrations (chemical methods) or of isotope (tracer) concentrations. The complexity and the detail level of the obtained results vary largely among the methods. Different methods commonly render very different results when applied to the same location (Benedittis and Bertrand-Krajewski 2005, Mitchell et al. 2007).

For the assessments in Tepic, it is considered that an approach based on several methods applied simultaneously would be suited best, in order to compensate for the data uncertainty and as a means to cross-check the results of the different methods. Due to the complexity and specialized know-how required for tracer methods, only volumetric and chemical methods have been considered.

As shown in Figure 7.3, infiltration and exfiltration can occur in the sewer depending on the groundwater level and the specific location of each pipeline section. For small catchment areas, it might be easy to recognize a prevailing condition. When the flow at the end of the pipe is less than the wastewater generation and the substance concentrations are not changed, a prevailing exfiltration is the most logical explanation. When the outflows of the sewer are larger than the wastewater generation and the concentrations have been reduced, a prevailing infiltration would explain the situation. In large sewer catchment areas, most of the time there will be a mix of infiltration and exfiltration in different pipeline sections or even at the same pipeline sections in alternate manner depending on groundwater level and rain conditions. For this reason, it is considered impracticable to try to measure I/I and exfiltration at the same time with volumetric or chemical methods.

In Tepic, the evidence of wastewater dilution at the entrance of the WWTPs and the necessity of constant by-passing the excess inflow to the river, supports the hypothesis of prevailing infiltration. However, due to the poor condition of the pipelines in some areas of the city, there is also a high risk of significant wastewater leakage to the groundwater when the groundwater table is low or from the higher areas of the city. Regarding the sewer exfiltration in Tepic, it is considered more important to focus the efforts in locating the exfiltration points and to eliminate them, than in actually measuring the exfiltration flows. Based on this reasoning, the objectives of the assessments in Tepic should be:

1. To assess the total I/I at the entrance of the WWTPs in dry weather and rainy weather in order to assess its impacts on the efficiency of the system.

2. To assess the prevailing leakage conditions in the sub-catchments of the sewer in order to determine their contribution to the total I/I and to detect the hot-spots for I/I and exfiltration.

➥ The information obtained from the assessments can be used to prioritize sewer repair activities and thus both I/I and exfiltration can be reduced simultaneously.

➥ A repetition of the I/I measurement after the improvement measures allows to assess their impact.

In the following section, a short explanation of the basic principles of volumetric and chemical methods for I/I measurements is presented together with a brief discussion of methods considered as feasible in Tepic. Specific considerations for the measurements in the city can be found afterwards.

Volumetric methods

The basic principle for volumetric I/I measurement as summarized by Benedittis and Bertrand-Krajewski (2005) is presented in Equation 7.1. The difference between the total sewer inflow Q_{tot} and the wastewater input to the sewer Q_{ww}, equals the infiltration volume Q_{inf}. The values of Q_{tot} should be obtained from volume measurements at the end of the sewer networks (the influent of the WWTPs). The values of Q_{ww} can be obtained from measurements or from estimations.

$$Q_{inf} = Q_{tot} - Q_{ww} \tag{7.1}$$

The measured data obtained during dry weather can be used in mixed systems to determine the Permanent Infiltration caused by groundwater infiltration (also known as Base Infiltration, BI). During rainy weather the measurements of the infiltration would include the groundwater infiltration and the inflows caused by the rain. The respective inflows, referred in this research as Seasonal Infiltration, can be obtained by comparing the results during dry weather and rainy weather.

Volumetric methods are normally based on Average Daily Flows (ADF) or on Minimum Daily Flows (MDF). The use of the MDF in some methods results from the assumption that most of the MDF (normally occurring at night) corresponds to I/I and not to wastewater. For example, the Wastewater Production Method is a very straightforward method for the I/I calculation which is widely used by practitioners in the USA. It assumes that the MDF occurring at night (typically between 12:00 midnight and 06:00 a.m.) represents a small pre-defined fraction of the total Q_{ww}.

The flow Q_{inf} is calculated in this method by applying equations 7.2 and 7.3. The factor X of the equations has been calculated by some authors as 0.88 and it implies that MDF represents 0.12 of Q_{ww}. Compared to other methods, this method seems to render higher results in average than other methods. For this reason some practitioners modify the factor X to achieve results more consistent with specific wastewater production patterns and according to the specific characteristics of the site (Mitchell et al. 2007) . For instance, in large catchment areas where the flow time towards a WWTPs is considerable or at locations where the industrial and commercial wastewater contributions to the sewer are substantial during the night, the X factor should be reviewed. Mitchell et al. (2007) recommend to use a conservative X factor not larger than 0.75.

$$Q_{ww} = \frac{ADF - MDF}{X} \tag{7.2}$$

$$Q_{inf} = ADF - Q_{ww} \tag{7.3}$$

To exemplify the Wastewater Production Method, a calculation of the Infiltration at the influent of the WWTP El Punto was made based on data provided for a dry month in 2007. Figure 7.5 shows the results obtained by applying an X factor of 0.88 and 0.75.

Other volumetric methods for I/I measurements calculate Q_{ww} from actual measured wastewater volumes, from drinking water supply data (Potable Water Use Method) or from theoretical wastewater production as found in registries or literature (Theoretical Wastewater Production Method). The use of ADF alone without consideration of the MDF seems appropriate especially for large catchment areas where the flow from the most distant locations towards the WWTPs is considerable or when there are pumping stations working in irregular intervals (LUBW 2007).

Some volumetric methods require continuous flow measurement at the influent of the WWTPs over the whole year. The reliability of the I/I calculation increases indeed when there is more data available. However, periods of 4-10 dry weather

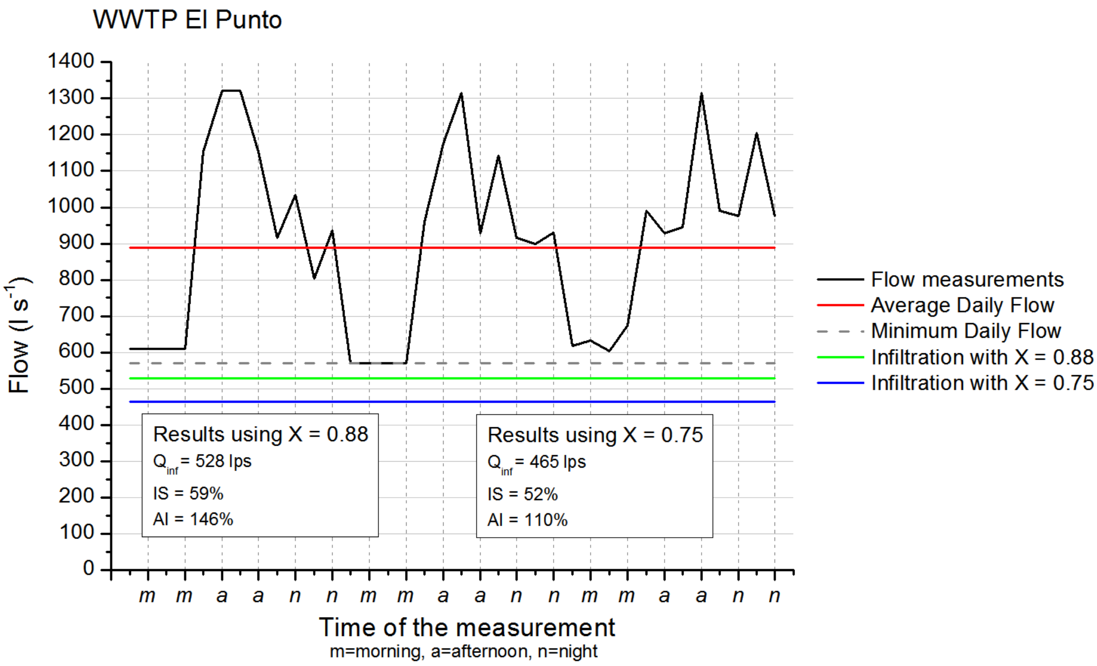

Figure 7.5: Example of infiltration calculation at the WWTP El Punto according to the Wastewater Production Method and using two different values for X.
Volume measurements obtained from Castillo Delgado 2007

days provide already reasonably reliable results (Benedittis and Bertrand-Krajewski 2005).

Chemical methods

The principle of the chemical method for I/I measurement is based on the assumption that the I/I enters the sewer system mostly unpolluted and uniformly during the day and dilutes the wastewater. For the chemical method developed by Hager et al. (1985), the following information obtained during dry weather is required (LUBW 2007):

- Average flow: $Q_{dw,a}$ (m^3 h^{-1})
- Minimum night flow: $Q_{dw,min}$ (m^3 h^{-1})
- Load of the selected parameter: S (kg h^{-1}).
- Average concentration of the selected parameter: $C_{dw,a}$ (mg L^{-1})
- Concentration of the selected parameter during minimum night flow: $C_{dw,min}$ (mg L^{-1})

Appropriate parameters are for example: Chemical or Biological Oxygen Demand (COD_{hom}, BOD_{hom}), Total Kjeldahl Nitrogen (TKN_{hom}), Phosphorous

($P_{tot,hom}$), Total Organic Carbon (TOC) and Total Suspended Solids (TSS). The concentrations of the parameters should be obtained from concentration curves elaborated from 2-hour composite samples (LUBW 2007). The calculation of the Infiltration Share in the sewer (IS, see definition in Section 5.3.3) is done based on Equation 7.4.

$$IS\ [in\ \%] = \frac{100}{m} \cdot [1 - s \cdot (m - 1 + c)] \tag{7.4}$$

where

$$m = \frac{Q_{dw,a}}{Q_{dw,min}}\ [dimensionless] \qquad c = \frac{C_{dw,min}}{C_{dw,a}}\ [dimensionless]$$

$$s = \frac{C_{dw,min} \cdot Q_{dw,min}}{S} \quad \text{and also} \quad s = \frac{C_{dw,min} \cdot Q_{dw,min}}{C_{dw,a} \cdot Q_{dw,a}}\ [dimensionless]$$

The chemical method of Hager et al. (1985) can be very exact. However, to obtain reliable results, a costly and time-intensive labour is needed, commonly requiring online flow and concentration measurement. A simplified version of the chemical method based on the daily measured average COD concentrations in wastewater has been developed and widely applied in Baden-Württemberg (Germany) with good results. For the simplified chemical method, the daily COD load per person and the expected wastewater production are used to calculate a theoretical COD concentration of the wastewater. A dilution curve is then established where the dilution of the COD is observed according to an increasing total water volume. From this graph, the corresponding I/I values for a specific measured COD value can be obtained. The COD should be derived from long term measurements (LUBW 2007).

To exemplify this approach, an I/I diagram for Tepic was created (Figure 7.6) assuming a daily COD load of 120 g person^{-1} (German average according to DWA 2008) and a daily wastewater generation of 187.5 L person^{-1} (obtained from multiplying the average per capita water consumption obtained in this study by 75%). The dilution curves established were used to calculate the infiltration at the WWTP La Cantera which is the smallest one in Tepic and which is expected to have a large (or the largest) percentage of household contribution compared to the other WWTPs in the city. Figure 7.6 shows the results.

The observed drawback of the simplified chemical method is that in presence of industrial contributions with large COD loads (such as those of the food industry) the I/I could be underestimated due to the increased COD concentration of the wastewater inflows. Additionally, when calculating the I/I in mixed areas with unknown COD contributions and unknown wastewater generation, the

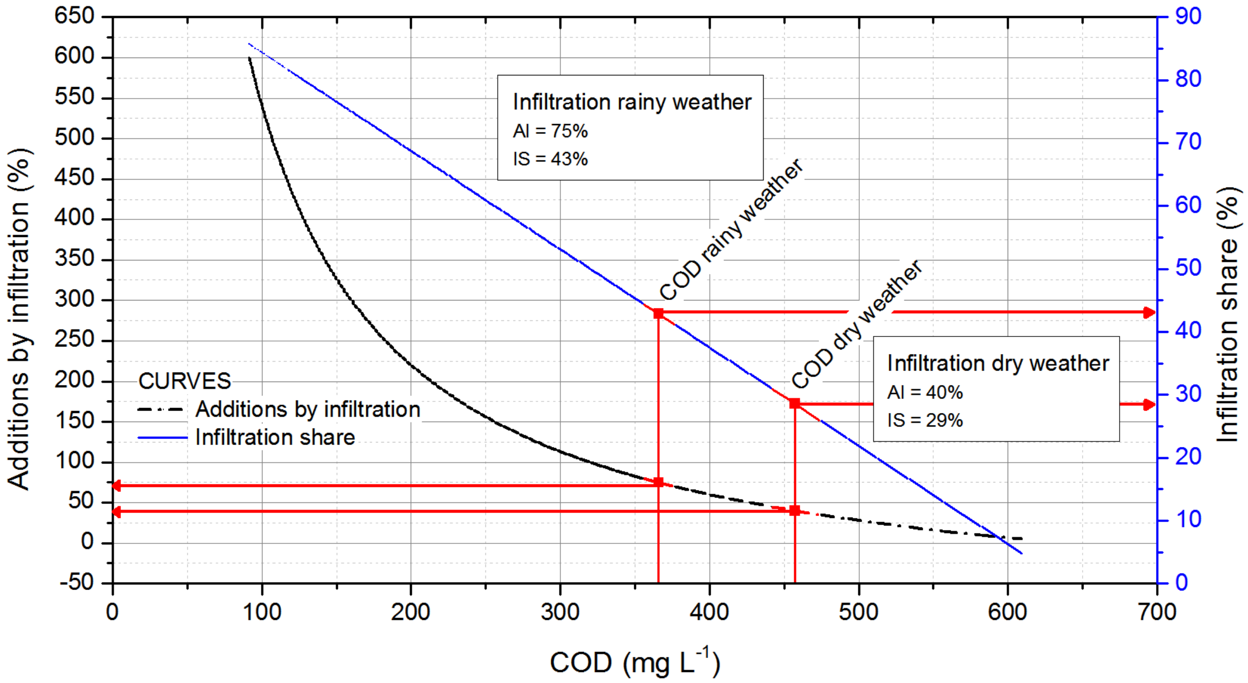

Figure 7.6: Assessment of the I/I at the inlet of WWTP La Cantera in 2011 according to the simplified chemical method. COD data at the WWTP provided by CONAGUA Nayarit.

uncertainty of the method increases. Thus, this approach seems most appropriate for calculating I/I in areas with predominant residential wastewater generation.

Suggestions for infiltration measurements in Tepic

It is suggested to apply the following three approaches for the measurement of the I/I in Tepic:

1. Wastewater Production Method with X factor adjusted to 0.75 (WWP-Method)
2. Simplified Chemical Method (SC-Method).
3. A variation of the WWP-Method in which the flow Q_{ww} is calculated based on potable water consumption and theoretical wastewater generation from registries (combined approach)

According to the last state of information, there are no automatic volume measurement devices at the entrance of the WWTPs. Measurements are done sporadically with mobile devices or manual methods. For the application of the WWP-Method and the combined approach it is a pre-requisite that either permanent or mobile flow measurement devices are made available.

The application of the WWP-Method and the combined approach requires that at least one measurement campaign is carried out for all WWTPs in order to obtain the baseline data for the hydrographs and to obtain the ADF and the

MDF. The data gathered during each measurement campaign can be used to apply both methods. It is recommended that the campaigns last a minimum of 5 days of dry weather flow[1]. Since Tepic is equipped with a separated sewer system, the assessment of the I/I should include measurements in the rainy season to calculate Direct and Delayed Inflows generated by rain events. At least a one week period should be assessed after a significant rain event[2].

Since the WWP-Method is based on night flow analysis and few measurements may tend to overestimate the I/I (Benedittis and Bertrand-Krajewski 2005), it is highly recommended to extend the duration of the measurement campaigns if possible to 8-10 days of measurements in both dry and rainy season. Longer measurement periods would affect the reliability of the results in a positive manner. Since the excess inflow to the WWTPs is bypassed to the river before entering the facility, all volumetric measurements (ADF, MDF) should be carried out before the by-pass point.

A weather station of the CONAGUA directly located in Tepic gathers information about precipitation. A plot of the precipitation data together with the data obtained from the measurement campaigns can be used to correlate the I/I with the rain events and to assess the time span during which the effects of a single rain event can be observed at the WWTPs.

For the application of the SC-Method, sampling and chemical analysis are carried out regularly at the WWTPs to control the inflow quality. The data is saved in the registries of the CONAGUA Nayarit. However, it is unknown how often these analyses are made and often the information about the sampling scheme or method is missing. It is also unknown whether the rain conditions during the days previous to the sampling were taken in consideration.

Therefore, a campaign to obtain composite daily samples in dry and rainy conditions is also necessary for the application of the SC-Method. The duration of the campaigns at dry and rainy weather can be the same as for the WWP-Method. To maximize time and resource efficiency, the sampling and analysis campaign should be ideally carried out at the same time as the volumetric measurements needed for the WWP-Method and for the combined approach.

The choice of parameter should be done for each treatment plant according to the characteristics of the users discharging wastewater to that facility. The parameter selection also has to consider the characteristics of the industrial wastewater discharged to the sewer. For example, when COD or BOD values are prone to be biased by the discharges of the food industry, perhaps TKN could be a more appropriate parameter. For the construction of the required dilution curves (see example in previous section, Figure 7.6), the parameter concentration in wastewater from domestic areas in Tepic can be calculated based on the

[1] To consider a day as "dry weather" at least three days should have passed without any rain event (EPA 2014)

[2] A significant rain event should cause surface ponding and runoff (EPA 2014).

available data or on literature data without incurring substantial mistakes. A much better approach could be achieved with new data experimentally generated by studies in households in the city.

The combined approach, analogue to the WWP-Method, is based on Equation 7.3. However, two different procedures are suggested for the calculation of the wastewater production Q_{ww} instead of the use of the MDF and the X factor as in Equation 7.2.

The first option is to calculate the Q_{ww} by means of the water supply data for each region of the city connected to a specific WWTP and by applying an appropriate "potable water to wastewater" conversion factor. The basic assumption is that there is clear information about the districts being served by specific groundwater wells. It is assumed that it is possible to clearly distinguish the water supply to each district and that these districts are the same districts connected to each WWTP. The procedure can be as follows:

- The actual water consumption rate of the users in Tepic is not measured on-site in most of the cases. However, the total volume of potable water supplied to the users is known from the macromeasurement at the groundwater wells of the SIAPA. Additionally, the REPDA contains information about the groundwater withdrawal of the industrial and non-industrial private users. The total groundwater input to a specific region of the city can be calculated from these data.

- The ratio "potable water to wastewater" can be considered to be 0.75 for Households and NI/ND users as suggested by CONAGUA (2007). The discharge of wastewater to the sewer may be considered as 100% of wastewater generation for regions with high degree of connection to the WW Sewer. For regions with low connection degrees, their discharge should be adjusted accordingly.

- For the industrial users, the calculation of their wastewater production can be made according to following premises: the water supply of the non-domestic users in the city by means of private groundwater wells is registered in the REPDA. Their permissions for direct wastewater discharges to the river are also found in these records. For a conservative calculation of their wastewater discharges to the WW Sewer, it could be assumed that all water which is not discharged to the river according to a corresponding discharge permission, is discharged to the public WW Sewer.

! Eventual adjustments for seasonal variations in the water consumption of industrial users must be made. For example, it is known that most of the activities for the sugar production in Tepic take place from November to February (H. XXXV Ayuntamiento de Tepic 1998).

! It might be that the actual wastewater discharges of industrial users are different from their allowed water withdrawal. For example, industries may withdraw more water than allowed, water may evaporate in the process, or it may remain in the produced goods. However, considering that industrial users are responsible for less than 10% of total water input to the city (see Figure 4.12), the error induced by the above premises is not considered to alter the results of the I/I assessment significantly.

! As a best practice, the information of the REPDA about water abstraction and wastewater discharges to the sewer of relevant industrial or NI/ND users should be verified directly with the user as far as possible.

If one or several single groundwater wells simultaneously supply districts connected to different WWTPs and the volume for each district is not measured separately, the calculation of the wastewater flow towards the WWTP under this first approach is not possible. The second approach can be implemented in this case although it implies a more theoretical calculation. The basic assumption is that there is clear information about the districts of the city connected to each WWTP. The procedure is as follows:

- With the information of the latest population census, the number of inhabitants in the districts connected to each WWTP is calculated.
- The wastewater generation of these inhabitants can be calculated by using the per capita water consumption obtained in this study or the water consumption mentioned in literature according to socio-economic level (CONAGUA 2007) and applying the water-to-wastewater ratio as in the previous approach.
- For non-domestic users, their wastewater discharge to the WW Sewer can be calculated as in the previous approach.

! The special indications mentioned in the first approach for industrial users should also be considered in this second approach.

The calculation of Q_{ww} under both of the above explained approaches should be compared and their probability should be analysed. For each WWTP, it should be evaluated which of the above approaches renders the best results for the calculation of Q_{ww}. Then, Equation 7.3 can be applied for the I/I calculation.

After the first assessments are made at the four WWTPs, the study is suggested to continue with the assessment of the sub-catchments. An analysis of the age and condition of the sewer as well as visual inspections can be used to prioritize the locations to be evaluated first. The measurements should be made at the end of each tributary section of a catchment area and before its connection to the main sewer. At this stage, the water volumes used for sewer cleaning should be checked with the local water works operator as well as the frequency and location of cleaning activities. It must be evaluated if these volumes are relevant for the total input to the catchment area of the sewer being evaluated. This issue becomes more relevant as the size of evaluation area decreases.

Once the I/I is assessed and the hot-spots are localized, a plan to improve the sewer conditions can be created. Additionally, measures can be taken to improve the overall efficiency of the system despite the existence of I/I.

7.2.3 Improvement alternatives

According to Decker (1998) the process of reducing the I/I can be summarized in three stages:

1. Identification of the sources of I/I
2. Realisation of technical measures to eliminate the current sources of I/I.
3. Planning of preventive measures to avoid future sources of I/I

Additionally, it must be considered what will happen to the water which will not be entering the sewer any more. The new path of these water flows should be assessed and measures for their correct drainage should be realised to avoid a shift of the problem to a different location (Decker 1998).

The quantitative methods described in the previous section are not only helpful to determine the I/I amounts, but also to determine the I/I sources (which can also be exfiltration sources) if applied to small sewer catchment areas. However, the qualitative methods are much more specific for locating the I/I sources. The qualitative methods include: visual inspections (man entry to a sewer is normally only possible when the inner diameter is at least 900 mm), closed-circuit television inspections, photographic inspections and ultrasonic inspections (Uibrig et al. 2002). In the case of inflow, the sources can be also detected by visual inspections of the external installations of the sewer, e.q. man hole covers.

Further methods to find I/I sources are smoke-testing and dye-testing. The first method involves pumping smoke through sewers from manholes and observing where smoke exits. The exiting smoke can indicate a broken pipe and can also identify where roof or foundation drains are improperly connected to the sewer system. For dye-testing a non-toxic fluorescent dye is poured for example from roof drains and then it is observed whether the color appears in the sewer. This provides verification that the storm drainage being tested is directly connected to the sewer (King County 2011). A summary for the procedure to be followed in order to minimize the I/I in public sewers is found in Figure 7.7.

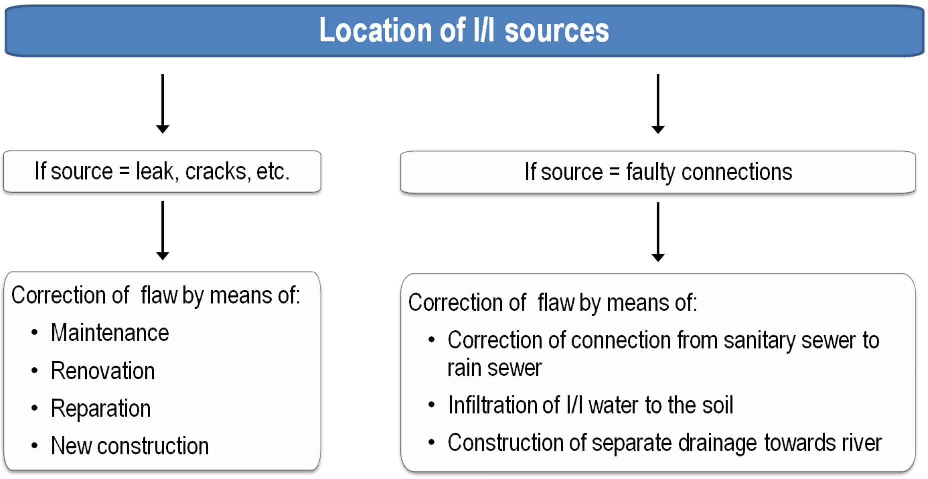

Figure 7.7: Procedure for reducing Infiltration and Inflow to sewer. Based on Decker 1998

It is very difficult and probably also uneconomical to eliminate completely all I/I. Therefore, it must be integrated in the planning and operation of sewer systems and WWTPs at least to some extent. The German technical literature includes several recommendations for the consideration of I/I in the dimensioning of sewers and WWTPs. For example, according to the technical standard DWA-A 118 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall), a I/I of 0.05–0.15 L s^{-1} ha^{-1} should be considered during the dry season for mixed or separated sewer systems. Additionally, for separated sewer systems, the I/I during rainy season can be assumed to be 0.2–0.7 L s^{-1} ha^{-1}. The standard DWA-A 118 makes it also possible to calculate the I/I as a portion of the total wastewater input (Q_{ww}). The total I/I can be considered to be in a range of 0.1 to 1 of Q_{ww}. This is equivalent to an IS of 10–50%. For dimensioning WWTPs, a maximum I/I of 0.15 L s^{-1} ha^{-1} can be included according to the standards ATV-Arbeitsblatt A 131 (Abwassertechnische Vereinigung ATV 1991) and A 135 (Abwassertechnische Vereinigung ATV 1989).

7.2.4 Impacts of reducing infiltrations and exfiltrations

To assess the potential impacts of reducing the I/I and the exfiltration, several scenarios were created simulating reductions of 10–50%. All simulations had the detailed scenario 2030 in common as basis for the modifications. In the model, the total I/I is composed of 5 different flows: the Permanent Infiltration, the AWI flow, the Infiltration from Soil, House Roof Inflow and Other Inflows. The last three flows together make up the flow Seasonal Infiltration (see Figure 4.6). For the simulations, the detailed scenario 2030 was modified with a 10% decrease in each of these flows (then 20%, 30%, etc.). Figure 7.8 shows the impacts of reducing infiltrations and exfiltrations.

The modelled reduction of the House Roof Inflow and Other Inflows from the Sealed Areas subprocess was done in a way that it resulted in an increase of the Stormwater Sewer Inflow, but not of the Runoff to Soil. It was done in this manner to avoid an increase in the flow Infiltration from Soil. With this approach, an increased infiltration from the soil to the sewer did not occur in the model (these flows are depicted in Figure 4.6).

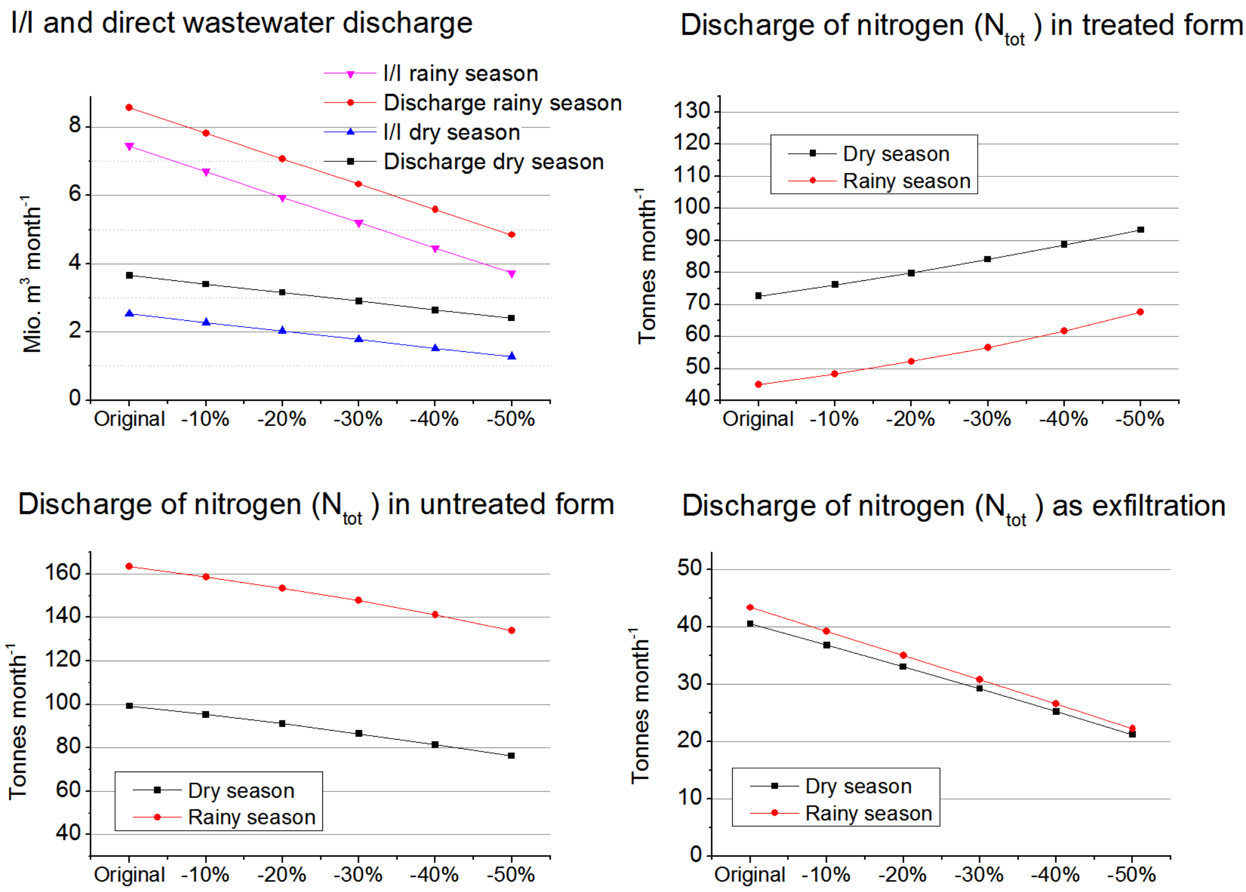

Figure 7.8: Impact of reducing the I/I and Exfiltration
The diagrams show the impacts of reducing the Infiltration and Inflow in the city as well as the Exfiltration. The X axis shows the simulated percentages of reduction.

The results indicate that the I/I and Exfiltration are reduced and consequently the discharges of untreated wastewater to the river are also reduced when actions are taken to improve the condition and efficiency of the sewer network. This is explained by the fact that the total volume of water entering the sewer will be less than before. It was observed that the decrease in the I/I has a 1:1 impact in the reduction of the direct discharges of wastewater. This result confirms that for reduction of the direct wastewater discharges it is more important to reduce the I/I than to reduce the water consumption. However, in none of the scenarios for I/I and Exfiltration reduction the direct discharge of wastewater is completely avoided. Even in a scenario without infiltration, the treatment capacity of the WWTPs would not be sufficient to treat all the wastewater of the city as it was already discussed in Section 6.2.3. Besides, eliminating the I/I in its totality is not feasible speaking in practical terms. Thus, it seems unavoidable to expand the current WWTPs or constructing new ones if the totality of the generated wastewater is to be treated before its discharge to the river.

Similar to the impacts of reducing water consumption, the reduction of the I/I and the Exfiltration have also a positive effect on the discharge of N in treated and untreated form. As the I/I and Exfiltrations are reduced, the discharge of N in untreated form is decreased and the discharge of N in treated form is increased. By analysing the figures, it was observed that during the dry season the effects of the I/I and Exfiltration reduction are very similar to those of the water consumption reduction. However, the reductions of the I/I and Exfiltration have a higher impact on N discharges during the rainy season.

The discharge of N as exfiltration to the soil and groundwater is reduced from approximately 42 tonnes N_{tot} month^{-1} in the original detailed 2030 scenario to about 22 tonnes N_{tot} month^{-1} in the 50% reduction scenario.

7.3 Improved rain water management

The use of rainwater for artificial groundwater recharge is a form of protecting the aquifer from depletion and of indirectly using the rain water for water supply. According to Government of Meghalaya (2004), the main advantage of storing rain water directly in the aquifer is that the construction of large storages is not required. Furthermore, the artificial recharge of groundwater with rain water is a means of storing water in times of water surplus for its later use in times of water shortage. Another advantage is the practical zero evaporation and the improvement of the water quality by soil-aquifer treatment or geopurification (Bouwer 2002). The groundwater recharge can be positively influenced by means of improved rain water management in cities. Improved practices can also help to be better prepared against flooding in the city and to avoid or diminish the seasonal infiltration to the WW Sewer (Espinosa Gutiérrez et al. 2013).

To characterize urban water and to illustrate the potential of rain water as a source for the supply of cities, Kenway et al. (2011) proposed the use of several indicators. Three of them are: supply centralization, rainfall potential for water supply and stormwater potential for water supply (Table 7.2).

The supply centralization of the city of Tepic is 86%. This means that 86% of the total water demand is obtained through centralized facilities of the water works company. Thus, there is a large reliance on public sources for the demand of water. The total rainfall potential for water supply at the location is 68%. This means that if all the rain was reused (for example by means of artificial groundwater recharge), a maximum of 68% of the total demand could be covered. The calculated stormwater potential for water supply is 48%. This means that a maximum of 48% of the total water needs of the city could be covered if the stormwater could be reused[3].

The obtained percentages of rainfall and stormwater potential should be considered as a maximum potential which is hard to achieve, since not all rainfall can be collected and not all stormwater can be used. There are however, a lot of technical and organisational measures that can be achieved to improve the rain water management in order to increase the groundwater recharge rate or to reduce the dependence on centralized water supply. Since the degree of consumption measurement in the city is very low and thus the water fees are not related to consumed volumes, it is considered that currently the users connected to the public mains have a very low motivation for implementing decentralized options of water supply by themselves.

Table 7.2: Indicators to characterize urban water

Indicator (units)	Calculation	Usefulness
Supply centralization (%)	Centralized supply ÷ Total water imports	Gives the direction to follow when choosing centralized or decentralized schemes of water reuse or of rain water harvesting.
Rainfall potential for water supply (%)	Rainfall ÷ Total water imports	It indicates how much of the water demand of the city could be covered directly by the rain (theoretically) if all rainwater was harvested. It is also an indicator of the total potential groundwater recharge.
Stormwater potential for water supply (%)	Stormwater* ÷ Total water imports	It indicates the maximal potential volumes of rainfall that can be actually collected for reuse purposes in the city.

*Stormwater is defined here as the part of the rainwater which runs off the sealed surfaces of the city. It depends on Rainfall volumes and sealing degree of the city among other factors.
Indicators and calculations based on: Kenway et al. 2011

7.3.1 Alternatives to improve groundwater recharge and avoid flooding

An investigation on the potential for groundwater recharge from rainwater and on the potential of improved stormwater practices in flooding avoidance was carried out for the city of Tepic within the framework of this research. A summary of the investigated alternatives to increase these potentials is provided below based on the work of Bardou (2012).

The alternatives for Tepic focus on rainwater infiltration since rainwater injection was considered an unnecessary expensive measure given that the aquifer at

[3]Indicators calculated based on the total water imports and centralized water supply obtained in the detailed scenario 2030, historical precipitation since 1977 and a sealing degree of the city of 70%.

the location is of unconfined nature. The technologies described below were considered as promising for Tepic based on the current city characteristics. Detailed explanations of each technology as well as a research on the suitability of these technologies for the city of Tepic according to its soil characteristics are provided in the full report of Bardou (2012).

Conversion of decommissioned dug wells as recharge shafts. There are several decommissioned wells in the city. They could be used as recharge shafts if the stormwater of the city is directed here instead of towards the main stormwater sewer or towards the river. This measure is recommended when a direct connection of roofs is possible because this is the cleanest stormwater. A regular cleaning of roofs becomes unavoidable in this case in order to secure the recharge with clean stormwater. If runoff from other more polluted surfaces is intended (e.g. runoff from streets), space for pre-treatment should be available because pretreatment becomes necessary. For selection of the appropriate locations, several factors are required to be evaluated. However, general recommendations are: the decommissioned well should be in favourable slope to avoid pumping and it should be far away from the river (in order to avoid base flow to the river instead of recharge to the aquifer). The useful life of such a recharge well depends on the quality of the stormwater. After some operation time, the decommissioned wells might become clogged by suspended particles of the stormwater, and a cleaning or its decommissioning becomes necessary.

Installation of dry wells (seepage pits) for runoff from roofs. At new development areas or during the renovation of old constructions, seepage pits can be installed to conduct the runoff from roofs to a small seepage pit next to the building. The infiltration of runoff from other surfaces of the building is also possible. This would not be appropriate at locations with shallow groundwater levels for example for buildings near the river.

Construction of vegetated swales at streets. Vegetated swales can be used for the temporal storage of rainwater, for its conveyance to infiltration devices, as pretreatment and as a means of natural infiltration. Their location could be at streets of new residential, commercial and industrial developments or near infiltration trenches. The use of low maintenance vegetation is recommended for keeping the cost at a minimum. This option for infiltration is not appropriate for shallow groundwater levels neither. To favour infiltration instead of conveyance, the swales should be placed on small sloped areas (2-6% slope) and small check dams can be added to the swale. The conveyed runoff could be also directed towards near-by infiltration trenches.

Use of pervious pavements. The use of pervious pavements instead of the conventional sealing for parking lots, streets, squares, sidewalks etc., can also improve the flow of rain water towards the aquifer. They are suitable for low traffic areas and they should be kept distant from industrial spill risks.

7.3.2 Impacts of improving rain water management

To assess the implementation impacts of the above mentioned modifications in the city, three scenarios were assessed. The scenarios considered low, middle and high engagement from the population and the governmental organisations according to the perception of what would be realistic for the city and considering also the observed attitude towards groundwater recharge measures in Tepic. Interviews carried out with the personal in charge of the rain sewer in Tepic at the city council, revealed that the population in general has a marked preference for conventional storm water solutions involving sealing of surfaces and conduction of rain water to the river instead of options involving on-site infiltration of rain. For example: it was mentioned that the citizens preferred completely paved streets than stone pavements. Stone pavements were perceived by the population as for "low socio economical" neighbourhoods. A change from completely paved streets to stone-paved streets would probably experience resistance from the citizens (Peña Fernández 2012)

The implementation of the suggested measures for improved rain water management were mostly allocated to the areas to be developed until 2030 and only a small fraction of the already constructed areas would experience a change. Table 7.3 explains the differences amongst the scenarios.

Table 7.3: Explanation of scenarios for groundwater recharge in Tepic by 2030

	Scenarios according to engagement level					
	Low		Middle		High	
Parameter↓ Location→	NA	AA	NA	AA	NA	AA
Number of recharge shafts		5		10		14
% of houses with dry wells	20%	0%	50%	0.5%	100%	5%
% of roads provided with vegetated swales and infiltration trenches	10%	0%	20%	0.1%	50%	1%
% of other surfaces[1] provided with vegetated swales and infiltration trenches	0%	0%	10%	0.1%	20%	1%
% of side walks provided with pervious pavement	30%	0%	50%	0.1%	50%	1%
% of other surfaces[1] provided with pervious pavement	5%	0%	30%	0.1%	80%	1%

[1] Parking places, private roads, squares.

NA: new development areas. AA: already developed areas.

The results of the scenarios are summarized in Table 7.4. It was noticed that even under the fulfilment of the challenging scenario the impacts are modest. The maximum additional groundwater recharge obtained under the challenging scenario would be equivalent to covering the needs of almost 40,000 people. However, this represents less than 5% of the yearly centralized water demand by 2030 and only 4% of the total water imports of the city. To avoid depletion of the aquifer, combined measures are needed including the reduction of the water demand and the increase of the natural groundwater recharge.

Furthermore, in the challenging scenario the implemented measures would only provide a 12.7% relief to the conventional on-site stormwater sewer. In other words, the implemented measures would only be able to manage 12.7% of the water during a rain event. The remaining water would have to be dealt within the conventional sewer system. To avoid flooding effectively and to improve the potential groundwater recharge, more engagement and adaptations are needed in the already developed areas. For this purpose, the engagement of community and users is a key success factor in any scenario since they should ensure proper maintenance of the decentralized facilities. Proper maintenance does not only guarantee the maximum profit of the constructed measures but it also may help to extend their life span. The involvement of the inhabitants is also essential to allow a flow of storm water to the facilities in the cleanest condition possible e.g. by keeping house roofs clean and streets and side walks free of garbage.

Table 7.4: Results of scenarios for improved rain water management

	Scenarios according to engagement level		
Parameter	**Low**	**Middle**	**High**
Goal 1: Avoiding depletion of the aquifer			
Maximum potentially infiltrated stormwater volume by infiltration devices per year[1]:	0.47 Mio.m^3	1.43 Mio.m^3	3.65 Mio.m^3
Compared to centralized groundwater demand in Tepic by 2030 (77.8 Mio.m^3):	0.61%	1.86%	4.74%
Equivalent to the annual consumption of:	5,186 PE	15,704 PE	39,963 PE
Goal 2: Avoiding flooding			
If devices designed to infiltrate a 6mm rain event[2], this volume would infiltrate per storm:	4,080 m^3	12,540 m^3	32,400 m^3
Relief of the rain water management system of the city per storm (as % of total to be managed):	1.6%	4.9%	12.7%

[1]Under the assumption that all infiltration devices are constructed with sufficient capacity for its inflow area. [2]Design storm in the city based on Peña Fernández 2008. PE: Person Equivalent calculated with a mean water consumption of 250 L per capita per day.

7.4 Wastewater reuse in Mexican context

The current conventional "end-of-pipe" technologies for sanitation have important drawbacks: high water consumption rates, resource depletion, high waste generation rates (e.g. sludge), increasing losses of valuable nutrients to the rivers parallel to the discharge of harmful substances to the environment and a high energy requirement for its operation (Lange et al. 2000). At the same time, wastewater is probably the only "natural resource" whose global availability is steadily increasing (Foster and Chilton 2004). Its production is reliably constant (Pereira et al. 2009). A logical consequence of these facts, is that the reuse of wastewater or of its constituents has become an increasing topic of interest in the past decades.

The reuse of wastewater can occur in several different ways and with different motivations. The motivation to substitute fresh water by wastewater can be for example to save water in regions where it is scarce, to save abstraction costs, to avoid water pollution or to make use of its valuable nutrient content. Another motivation for the reuse of wastewater or of excreta is the generation of energy by means of biogas production.

The scale of the wastewater reuse applications varies largely. Decentralized small scale options are based in the separation of certain flows in households for its later reuse on site with or without previous treatment. An example is the collection of gray water[4] at homes for its reuse for toilet flushing (Lange et al. 2000, DWA 2008) . Large centralized schemes can even go for a high-tech approach in which wastewater is treated and conditioned to drinking water standards, as in the NEWater project in Singapur (BASF SE 2013).

The MWA 2030 has as a long term goal (later than 2030) the complete reuse of wastewater. The proposed uses of the treated wastewater are in agriculture, in industry, for artificial recharge of aquifers or other water bodies and for irrigation of green areas (CONAGUA 2011). Currently, the most common reuse purposes of treated wastewater in Mexico are for industry and agriculture. The CONAGUA has been promoting actively the reuse of wastewater through different federal programs. As a result, the reuse of treated wastewater has increased from 25.4 $m^3\ s^{-1}$ in 2007 to 86.2 $m^3\ s^{-1}$ by the end of 2013.

The direct reuse of untreated wastewater is also permitted under certain conditions (CONAGUA 2014). The amount of untreated wastewater that was used in 2008 in Mexico was 133 $m^3\ s^{-1}$; almost five times larger than the reuse of treated wastewater (calculation based on CONAGUA 2014 and CONAGUA 2011). At present, a total of 260 $m^3\ s^{-1}$ of treated and untreated wastewater is estimated to be reused (Estrada Corona 2011). Considering the 86.2 $m^3\ s^{-1}$ of

[4]Grey water is defined as all domestic wastewater except for those of the toilet which contain excreta (Lange et al. 2000)

reused treated wastewater in 2013, the application of untreated wastewater for reuse is still twice as much.

Blanca Jiménez, a leading scientist for water issues in Mexico working at the National Autonomous University of Mexico (UNAM) and Vice-Chair of UN-Water, considers that the reuse of wastewater in the country is very important. The amount of available water does not change but the population is increasing. The growing population needs increasing amounts of water in households and also more food which in turn requires water for its growth. The water reuse in Mexico is considered as a feasible option to cover these growing needs, especially when reused at a local level (Estrada Corona 2011).

However, the reuse of wastewater is a controversial topic. Excreta and Wastewater contain indeed valuable nutrients such as nitrogen and phosphorus which are necessary for the growth of plants. Besides, if not only excreta is recycled but wastewater as a whole, it becomes a valuable water resource which is especially appreciated in arid regions (Feachem et al. 1983). However, it may also contain other substances such as salts, pathogens, chemical substances, pharmaceutical residues and hormone residues which can negatively affect the ecosystems and human health in immediate form or in the long term (Feachem et al. 1983, Patterson 2001).

Recent research indicates that pharmaceuticals and hormonal residues in wastewater (so-called emerging pollutants) have a negative impact on the environment and they can have a toxic or endocrine effect on aquatic flora and fauna. Besides, they contribute to the formation of antibiotic resistant bacteria (Tränckner and Koegst 2011). The emerging pollutants can be found in wastewater even subsequent to its treatment. Conventional wastewater treatment plants are not designed to remove these substances, so they are only randomly removed during the treatment (Jimenez 2009). Especially in the dry season, the concentrations of these pollutants can exceed the precautionary (and non-regulated) health-oriented guidance value (HOGV) of 0.1 μg L^{-1} (Meyer and Otterpohl 2014, Meyer et al. 2014). However, measuring emerging pollutants is not a common practice given the high costs implicated and the difficulty for obtaining "clean samples" (Jimenez 2009). Furthermore, their removal under advanced treatment schemes such as ozonisation, activated carbon or Advanced Oxidation Processes (AOP) does not only increase the costs of treatment but sometimes it is also insufficient to achieve the HOGV limits (Tränckner and Koegst 2011).

A main concern and an important target for developing countries in topics of water pollution should be precisely the **safe** reuse of the wastewater (Jimenez 2009). Jiménez (in Estrada Corona 2011) indicates that the highest wastewater treatment standards are not always necessary. Wastewater should be only subjected to the pretreatment necessary to meet the standards of its planned use.

Considering the evidence of the risks of reusing wastewater and facing the increasing aquifer depletion and water stress in Mexico, a profound risk-benefit analysis at the location is the most appropriate approach to make a balanced decision for any wastewater reuse activity.

The potential of wastewater for water supply can be calculated by comparison of the wastewater flow with the water demand (according to Kenway et al. 2011). The present research calculated a wastewater generation in Tepic by 2030 of 4.23 Mio. m^3 $month^{-1}$ and a water demand of 4.54 Mio. m^3 $month^{-1}$. Thus, if all wastewater would be recycled, more than 90% of the water demand in the city could be covered. However, not all wastewater can be recovered in a cost-efficient manner and not all wastewater is suitable for reuse.

During the site visits in Tepic and the interviews carried out at the CONAGUA Nayarit and SIAPA Tepic, it was observed that some untreated wastewater of the city is already being used directly on near-by agricultural fields. However, no records were found about the volumes used. The treated wastewater was not directly reused as it was discharged to the river. However, there was evidence that the river is used as a source for irrigation water on downstream agricultural fields.

In the following sections, general relevant aspects of wastewater reuse in Mexico are discussed focussing on the reuse of wastewater in Tepic at homes and in agriculture, for groundwater recharge and for biogas generation. It must be pointed out that the discussion is not meant to recommend a specific reuse purpose of wastewater in the city but rather to highlight the potential benefits and special considerations of each of the options. Only a detailed evaluation of each of these options and their requirements and modalities for implementation in Tepic can determine the best reuse application. However, it is considered that commonly a mix of several reuse options at different scales and locations in the city would render the most beneficial results.

7.4.1 Wastewater reuse at households

The reuse of wastewater or excreta at household level is not very common in Mexico. The preferred option for handling wastewater and excreta is the connection to a sanitary sewer. The national coverage rate currently is 91% of the total population. The goal of the national and local government is to increase the connection rate in urban areas and in rural areas as well (CONAGUA 2014). In Tepic the connection average is already 98%.

The population without connection to the sewer has either no improved sanitation facilities or they rely on low-tech sanitation concepts. The application of ecological low-tech concepts in domestic sanitation has achieved a certain acceptance and acknowledgement in Mexico, especially in the rural context. For example, there are currently numerous private companies offering products for the reuse of greywater, the construction of dry toilets or for biogas generation devices. Among the alternative technologies, the use of dry toilets (with or without composting of excreta) enjoys a certain popularity and there is a relative large number of companies producing them (CONABIO 2009). Nevertheless, the implementation of such ecological concepts seems to remain largely at the stage of pilot projects in rural areas. Relevant supporters in the past in Mexico have been the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ), the *Sarar Transformación*, the *Centro de Innovación en Tecnología Alternativa, A.C.* (CITA), *Espacio de Salud* (ESAC) and the Resource Institute for Low-Entropy Systems (RILES). In spite of the positive developments in implementing closed-loop and ecological concepts at households, the dominant tendency in Mexico is still that of conventional sewers and centralized wastewater treatment.

The implementation of source-separating schemes or water recycling concepts at household level is considered to have low success chances in the short or middle term in a location like Tepic, where most of the population counts already with a connection to water mains and to the sewer. The population without water supply and sanitation services expect also a connection to the water mains and to the sewer.

Besides, as already mentioned in section 3.2, currently the water fees are not related to the actual water consumption. Therefore, it is considered that domestic users have a very low motivation for implementing decentralized options of water recycling. However, there are areas of the city where the water supply is intermittent and in some cases insufficient to guarantee the satisfaction of the users. For these neighbourhoods, an approach for grey water reuse in non-sensitive uses such as toilet flushing could find a certain acceptance. The use of low-cost technologies would improve its implementation chances, since the users would have to pay for the installation and operation costs by themselves.

Ecological options for wastewater reuse (or for water saving) can also be implemented in Tepic in the course of new developments if enough acceptance from the user side is provided and the users are also supported with training in the use of the technology (Velarde Raudales 2011). Innovative ecological toilets with modern designs and with the comfortability of conventional toilets can improve the acceptance from users for being provided with an ecological concept or excreta reuse. A good example is found in the terra-preta toilet designed by the German industrial designer Sabine Schober. This toilet is one of the latest developments in the research of Terra Preta Sanitation (TPS). The TPS concept uses excreta which have been sanitized with lactic-acid-bacteria and which are mixed with charcoal for the production of highly fertile soils useful in agriculture and in reforestation (TPS-Initiative 2014).

Furthermore, the work of Ziedorn et al. (2008) shows that decentralized wastewater management options can also be implemented in existent urban infrastructure under consideration of the specific building characteristics. This becomes especially interesting for the creation of pilot projects in public buildings or facilities in Tepic with the goal of the reuse of wastewater and its constituents. This is considered to have a very positive effect in improving environmental awareness in the society as it represents a clear sign of commitment of the authorities to conservation of resources.

7.4.2 Wastewater for groundwater recharge

Overall, the storage of treated wastewater in the aquifer has been recognized as one of the best overall options when demand for irrigation water exhibits large seasonal variation (Foster and Chilton 2004). Therefore, another option for wastewater reuse in Tepic could be the artificial recharge of the aquifer.

Groundwater recharge with wastewater can occur intentionally or unintentionally. Unintentional or indirect recharge takes place from leaking sewer systems, from on-site sanitation facilities or by means of the excess irrigation of agricultural fields with wastewater (Foster and Chilton 2004). Intentional recharge takes place when infiltration or injection facilities are constructed for this purpose.

The Mexican standard NOM-014-CONAGUA-2003 (SEMARNAT 2009) was created to regulate the artificial recharge of aquifers with treated wastewater[5]. It considers the recharge feasible, as long as the wastewater does not alter the original quality of the water in the aquifer or as long as a treatment can be provided to avoid pollution risks. This standard considers the soil and subsoil as a natural treatment layer that can be of use when combined with appropriate pre-treatment of the wastewater. The quality requirements for the wastewater to be used for recharge and the distances to drinking water abstraction points are depending on the recharge schemes. A superficial recharge has to fulfil less stringent guidelines than the direct recharge. Regarding the substances and concentrations allowed in the wastewater, the requirements refer to the limits mentioned in the Mexican standard NOM-127-SSA1-1994 (Secretaría de Salud 1996) which are the same as for drinking water. Moreover, NOM-014-CONAGUA-2003 includes an additional list of pollutants which are not yet regulated by any other Mexican standard stating the allowed concentrations for the recharge of aquifers. The additional list includes microbiological pollutants, organic and inorganic compounds, disinfectants and radioactive elements. Pharmaceutical and hormonal compounds are not included in the list.

Besides fulfilling the wastewater quality requirements, the projects for groundwater recharge have to comply with several requirements with respect to operation

[5] A different Mexican standard, the NOM-015-CONAGUA-2007 (SEMARNAT 2009) specifies the requirements for the artificial infiltration of water into aquifers when rain is the water source.

and monitoring. In sensitive cases, the realisation of additional hydrogeochemical and toxicological studies is required before the implementation of the recharge.

The results of the simulations in this research indicate that by 2030 the water demand of the city of Tepic alone will be larger than the natural recharge of the aquifer. Many other settlements and agricultural activities depend on the same aquifer so that the depletion seems to be inevitable. Therefore, the artificial recharge with the effluent of the WWTPs seems to be an option worth to look at.

It is unknown to which extent the current quality of the WWTP effluents in Tepic complies with the requirements of the NOM-014-CONAGUA-2003. It can only be guessed that the current quality will probably not meet the standards for groundwater recharge, given that the WWTPs have not been designed for meeting stringent restrictions. Currently all kinds of users, including industry and hospitals, are discharging to the public WWTPs. However, if the goal is to recharge the aquifer with treated wastewater reuse and if the soil and aquifer conditions allow for the recharge, the WWTPs should be adjusted or equipped with additional technology to remove the pollutants of concern provided that enough area is available for the installations. Probably a better approach, and also a cost-effective one, would be to identify the sources of persistent or emerging pollutants and apply on-site measures for their control or elimination where they are still concentrated instead of treating them after they are diluted together with the domestic wastewater.

Additionally, in conditions of deep groundwater levels as in Tepic, the passage of the wastewater through the vadose zone is likely to have a positive effect in the wastewater quality by eliminating most pathogens (Foster and Chilton 2004). Nevertheless, several barriers are recognized for the reuse of treated wastewater for the recharge of the aquifer:

1. In Tepic, the industrial wastewater is predominantly discharged to the public wastewater sewer and a pretreatment of the discharge is not guaranteed. The industrial wastewater quality regarding heavy metals, organic and inorganic compounds and regarding emerging pollutants is unknown. Thus, if the effluents of the WWTP are to be used for groundwater recharge, the best would be to choose WWTPs with the lowest discharges from the industry and hospitals or to separate these discharges from the public sewer.

2. The WWTP with the largest effluent is located at the northern borders of the aquifer. The groundwater flow is in direction Northwest. The recharge with this effluent might not be technically possible or it may be very costly.

3. It has been observed that elevated dissolved organic carbon (DOC) concentrations in wastewater will potentially form harmful trihalomethanes (carcinogenics) when the water is disinfected (Foster and Chilton 2004). In

Tepic, the last step of all four WWTPs is chlorination. This is as well the only conditioning treatment given to groundwater for drinking purposes. Studies should be made to determine the amount of DOC in wastewater, to reduce it and to replace chlorination by other disinfection means.

4. Even under conditions of best available technology and best management practices, the population in Tepic might not agree in the recharge of their water supply source by means of wastewater infiltration. Environmental awareness rising must accompany the groundwater infiltration project.

7.4.3 Wastewater use in the agriculture

The reuse of wastewater as sewage or sludge for irrigation or fertilization of green areas or agricultural fields has many advantages. It is an alternative nutrient and water source for plants and it contributes to the conservation of fresh groundwater. It may also help reducing costs, since less artificial fertilizers are bought and groundwater pumping costs are avoided. It also decreases the amount of nutrients being discharged to the river and helps avoiding eutrophication of rivers, when the treated wastewater is directly conducted to the areas to be irrigated.

However, since the irrigation of agricultural crops with wastewater can be a source of uncontrolled aquifer recharge, caution must be taken that there will be no excess irrigation and that safe loading rates and patterns are used (Foster et al. 1987, Foster and Chilton 2004). Furthermore, there is evidence of an increase in gastro-intestinal diseases when non-treated wastewater is used for irrigation purposes (Blumenthal and Peasey 2002, Jimenez 2009). Besides, when industrial effluents are included in the wastewater, there are also long-term risks such as accumulation of toxic elements in the soil, reduction of soil fertility and the up-take of harmful substances in the food-chain (Foster and Chilton 2004, Buechler et al. 2006). In general, it can be said that the use of untreated wastewater involves a great risk to public health and should not be allowed (Feachem et al. 1983).

Besides the use of tertiary treatment for wastewater (disinfection or extended retention in maturation ponds), the WHO recommends additional measures to manage the health risks linked to wastewater reuse as e.g. the choice of appropriate irrigation techniques. Sprinkler irrigation has the highest potential to spread bacterial and viral diseases and thus a minimum buffer zone to houses and roads should be implemented and farmers should wear protective clothing. The selection of appropriate crops plays also an important role: water of poor quality can be used for non-edible crops or for crops which are cooked before consumption (Buechler et al. 2006). Alternatively, innovations in sanitation systems could be used to recover the water and the nutrients from the wastewater streams in decentralized schemes by means of ecological sanitation concepts at homes (known as Ecosan) or by means of closed loop approaches at the industry (found for example in the Zero Emissions Research Initiative, ZERI). In centralized schemes, the nutrients can be recovered from wastewater or from the wastewater sludge by means of precipitation, biological P-removal or adsorption to zeolites.

The Mexican regulations provide a clear legal framework for the reuse of wastewater. The standard NOM-001-SEMARNAT-1996 (SEMARNAT 1997) specifies the pollutant guidelines in treated wastewater that allow its reuse for agricultural and other purposes. The standard NOM-004-SEMARNAT-2002 (SEMARNAT 2003) specifies the maximum allowable limits for reuse and disposal of wastewater sludge and biosolids. However, the use of untreated wastewater in agriculture is still a common practice in the country.

In Tepic it is recommended to use exclusively treated effluents for irrigation. Especially when the irrigated crops are for raw consumption, this is of key importance. Similar to the recommendations in the previous section, it should be evaluated what kind of industrial streams are discharged to the public WWTPs and critical flows (e.g. those of chemical industries, hospitals, etc.) should be separated from the public network or they should receive a proper pretreatment before their discharge.

The motivation to reuse wastewater in agriculture answers to three factors: there should be wastewater available, there should be a (local) demand for it and the cost of reuse should be affordable. Two separate studies were made within the framework of this thesis to evaluate the potential demand for N and P in the agriculture of Tepic (Rivera 2011) and to evaluate the potential for N and P recovery from the wastewater streams of the city (Suanno 2011).

The results of Rivera (2011) about the potential N and P demand[6] in the local agriculture indicate that for the 57 ha of agricultural fields cultivated in the municipality of Tepic by 2007, approximately 4,800 tonnes N year^{-1} as well as 1,700 tonnes P year^{-1} were required.

The future potential N and P demand for agricultural activities was calculated under two approaches. The first approach was based on the production potential (under optimal conditions) of agricultural activities as calculated by Gonzalez et al. (2012). The results of the calculations under this approach show a potential total demand of 8,679 tonnes N year^{-1} as well as 7,045 tonnes P year^{-1}. This is considered an optimistic, yet, realistic calculation.

A more general and ambitious calculation was carried out based on the total potential expansion of the agricultural areas in the municipality of Tepic as calculated by INEGI (2009). The results of the calculations under this different approach show a potential total demand of nearly 11,700 tonnes N year^{-1}

[6] The calculation is based on the data about fertilizer application and fertilizer composition available for 2007, not on plant requirements

and 3,700 tonnes P year^{-1}. These last figures include a potential demand of domestic agricultural activities of approximately 2,500 tonnes N year^{-1} and 1,500 tonnes P year^{-1}[7].

The demand for N and P may be obtained from wastewater derived products. Suanno (2011) investigated the potential technological options for the recovery of N and P the wastewater streams. His results point out that a combination of adsorption and precipitation processes for N and P removal at the discharge line and the sludge line of the WWTPs in Tepic could be a good option considering the installations already in place. Furthermore, direct urine application could be used for the recovery of N and P from decentral sanitation and for domestic crop growth. Through a literature research the theoretical removal coefficients for each of the selected technologies was documented. The documented recovery rates vary widely, however, an N recovery rate in average larger than 60% (in some cases up to 80%) and a P recovery rate larger than 70% (in some cases up to 97%) was observed.

The total input to WWTPs calculated in the basic scenario 2030 was 1,713 tonnes N year^{-1} and 356 tonnes P year^{-1}. The households with decentral sanitation (candidates for urine collection) generate only 36 tonnes N year^{-1} and 7 tonnes P year^{-1}. If the N and P contained in the totality of the generated wastewater in the city is considered and not only the N and P in the influents of the WWTPs, the N and P amounts to 2,824 tonnes N year^{-1} and 593 tonnes P year^{-1}. This is far below the current and the potential demand. This means that even under the best nutrient recovery scheme or by a total wastewater reuse in agriculture, the N and P requirements of the agriculture in the municipality cannot be met. Paradoxically, this fact is an important reason to support the reuse of wastewater for the agriculture. Since the demand is so large, it would be the most sustainable decision to provide as much as possible of the required nutrients from local renewable sources.

It is worth to discuss the possibility that an over-fertilization of the soil may currently take place so that the calculated current and potential demand may be overestimated. Furthermore, since the demand was calculated based on fertilizer application and not on actual plant requirements, the actual requirements could possibly be lower. Lastly, the plant availability of the nutrients in different fertilizers differs and thus the same amounts of nutrients in different fertilizers can have a different uptake rate in plants. More research at local level is needed to determine which kind of anthropogenic fertilizer could provide the best yields and the safest application.

Considering the general benefits of wastewater reuse in agriculture, which are not only related to their N and P content but also to the water replacement potential and monetary savings for the farmers, the reuse of wastewater in

[7] Amounts corrected *Ex Post*

agriculture is an approach worth to pursue. The recovery of nutrients from the wastewater flows by means of adsorption, precipitation or crystallization seems to be a more secure method in order to reduce potential hazards to human health. However, this is also the most costly option.

For the agricultural reuse of wastewater, it would be optimal that the nutrients are preserved in the wastewater flows and not removed. At the same time, removal of persistent organic compounds (emerging pollutants) and a disinfection are recommended in order to allow the application of the treated wastewater to a broad range of crops. However, further research is needed in this kind of treatment schemes where nutrients are conserved but emerging pollutants are removed (Meyer et al. 2014).

7.4.4 Wastewater use for biogas generation

The production of biogas from the sludge of wastewater treatment plants is another modality of wastewater reuse. If the residual sludge from a WWTP is subjected to anaerobic treatment, a mixture of methane, carbon dioxide and other gases is formed known as biogas. Biogas can be also the product of the anaerobic decomposition of black water[8], faecal sludge, liquid manure and solid organics. The obtained biogas can be used for power generation and be useful at the same location or in the surroundings (Feachem et al. 1983, Velarde Raudales 2011).

Biogas can be produced from separated wastewater flows in small scale under decentralized schemes. For example, the project "KREIS" for energy recovery and waste water management at the newly developed settlement in Jenfelder Au (Hamburg, Germany) demonstrates how human excreta, kitchen waste, grease residues and lawn waste can be used at neighbourhood level for biogas generation besides using water recycling concepts for water saving (Bauhaus-Universität Weimar 2015). Closed black water cycles for the generation of biogas and compost from households are also an option (Antholz et al. 2009). Low-tech biogas production is also possible from households wastewater or from organic material and excreta. The work of Velarde Raudales (2011) includes a technology review for low-tech biogas generation. The biogas generated in this way can be used for cooking in especially designed biogas burners.

Biogas can also be produced in large scale at the WWTPs. In Germany, for example, at more than 1,000 wastewater treatment plants biogas is produced by digestion of sludge and converted to 4,500 GWh year^{-1} of electric power (Kempter Regel et al. 2010, Blesl and Ohl 2010). In Mexico, the production of biogas is already applied at numerous locations. However, the applications

[8]Black water: mixture of excreta (urine and faeces) and flushing water along with anal cleansing water + dry cleansing material (Velarde Raudales 2011)

have been concentrated on biogas generation from agricultural residues and from landfills and not on biogas generation from wastewater or wastewater sludge (Masera Cerutti et al. 2011).

The potential for biogas generation from wastewater in Mexico has been calculated to be 4.18 PJ year^{-1} (1,161 GWh year^{-1}) if all collected wastewater could be treated and biogas would be generated from it (data for 2003: Arvizu Fernandez and Huacuz Villamar 2003). The advantages of biogas generation at the WWTPs are several: it is an alternative to the conventional disposal of wastewater sluge and it may help to cover the energy requirements of the treatment facilities. It may help to save energy and economic resources (Espinosa Gutiérrez 2007). Therefore, it is concluded that biogas production is another promising option which is worth to be looked at in the course of evaluating potential reuse applications for the wastewater in Tepic.

Chapter 8

Conclusions

The application of urban water balances and similar approaches for the integral evaluation of urban Water and Wastewater Management Systems is largely unexplored in Mexico. The results of the present study demonstrated that Material Flow Analysis (MFA) can be effectively used for the realistic assessment of the water inputs and outputs of a city in terms of volumes as well as in terms of nutrient loads. It can also be used as a tool for comparison of the situation before and after system modification it helps to assess the impacts of implemented improvement measures under a holistic approach.

The use of good quality input data in terms of reliability and actuality is decisive to obtain plausible results since the quality and accuracy of the results of the balances is a function of the input data. However, even under conditions of data uncertainty and scarcity it is possible to perform an MFA of the system if the use of available data is maximized. The uncertainty in the calculated flows is tolerable when the purpose of the evaluation is to identify the current trends in the system and when the goal is to obtain a first estimation for flows which, otherwise, are difficult to be measured directly. Furthermore, by modelling conservative scenarios, uncertain flows are calculated as minimum potential values. This is helpful to avoid alarmist calculations which can be a barrier for the acknowledgement of the model results from the side of the system operators.

The assessment of the WWMS of Tepic by means of MFA provided new insights into the water metabolism of the city. The created model showed the paths that both water and wastewater follow in the city and a complete balance of the water inputs and outputs in the city as well as balances for nitrogen and phosphorus were made for the first time. The interactions between the different consumption, pollution and transport processes for water in the city were also recognized.

The comparative evaluation of scenarios for the city simulating the conditions in years 2007, 2011 and 2030 allowed the evaluation of the impacts of recently implemented improvements and the evaluation of improvements to be implemented in the coming years. Besides identifying a current trend of high water consumption it was also found that there is a high dependency on centralized supply and that households are the most important user type in terms of wastewater generation as well as nitrogen and phosphorous input to the WWMS.

It was also found that the planned improvement measures (Table 3.2) were not sufficient to avoid the direct discharge of wastewater to the river or to provide treatment of all generated wastewater. The unplanned infiltrations of undesired water to the wastewater sewer are largely responsible for this and are currently largely underestimated. Furthermore, it was found that despite the installation of new WWTPs the total export of N and P to the environment remains almost unaltered and only a shift of the discharge paths was observed. This is because no nutrient removal schemes are on place.

The detailed assessment of the situation in 2011 allowed for the evaluation of the infiltrations to the wastewater sewer. These were found to be a significant flow contributing to the total water input into the sewer. The infiltrations vary according to dry and rainy conditions being larger during the rainy season. They affect the sewer performance in a relevant manner and diminish the wastewater treatment coverage in the city significantly. The infiltrations also affect the exports of N from the city to the environment by increasing the N exports in untreated form to soil and river when the infiltrations are larger during the rainy season.

A detailed projection of the situation in the city by 2030 was made under consideration of the newly generated knowledge of the water metabolism of the city and of the improvements planned in the WWMS. Following main challenges were encountered in terms of water and wastewater management:

- High water consumption.
- Large discharge of untreated wastewater to the environment.
- Large exports of nitrogen to the water and soil/groundwater (in treated and untreated form).

To counteract the recognized challenges, it was proposed to decrease the water consumption, to decrease the infiltration and exfiltration rate, to improve the rain water management and to reuse wastewater.

The use of a modelling approach demonstrated to be suitable for simulating the impacts of several proposed solutions before decisions are made. With this information, city planners and decision makers are better prepared to implement successful strategies to increase efficiency in water use and to avoid further pollution of the water bodies. This facilitates effective contributions for a sustainable growth.

With this in mind, the potential impacts of several improvement measures were simulated. The results of the future improvement scenarios indicate that a reduction of the current water consumption rates is needed in order to avoid the depletion of the aquifer. The reduction of the water consumption produces an increase in the discharge of N in treated form whereas the discharge of N in untreated form decreases. In other words, the export of N to the environment in its most toxic form decreases. The effect is more pronounced in the dry season, when the infiltrations to the sewer are also lower. The volume reduction in the sewer will result in higher pollutant concentrations in the wastewater and adjustments in the wastewater treatment plants could be eventually required.

The conclusion of the scenarios for the reduction of the infiltration and exfiltration is that to decrease the direct wastewater discharges it is more important to reduce the infiltrations to the sewer than to reduce the water consumption. However, in none of the scenarios for infiltration and exfiltration reduction, the direct discharge of wastewater is avoided. Even in a scenario without infiltration (which is unrealistic), the treatment capacity of the installed WWTPs would not be sufficient to treat all the wastewater generated by the city in 2030. Besides the reduction of the infiltrations and the expansion of the wastewater treatment facilities or the construction of additional ones, alternative measures can provide a relieve to the WWMS. For example, the reduction of the water consumption together with the application of ecological sanitation concepts and zero emission concepts can help to reduce the generation of wastewater or to promote its reuse as a valuable resource.

The improvement of the rain water management in the city can help to recharge the aquifer and also to avoid flooding in the city. However, to avoid flooding effectively and to improve the potential groundwater recharge, adaptations are needed mostly in the already developed areas of the city. With respect to this issue, the engagement of community and users is a key success factor in any scenario.

There is also a large potential for the reuse of wastewater in the city and it is considered that a mix of several reuse options at different scales and locations in the city would render the most beneficial results. There are several potential uses: at household level the reuse of wastewater may substitute freshwater or it can be used as fertilizer for domestic agriculture. In the large scale it can also be used for the artificial recharge of groundwater under compliance with Mexican and international guidelines. It can also be used as water and nutrient provider for local agriculture or even for biogas generation. According to each selected reuse and scheme, there are higher or lower health risks to be minimized. Under the evidence of the risks of reusing wastewater and facing the increasing aquifer depletion and water stress in Mexico, a profound risk-benefit analysis seems the most appropriate approach to make a balanced decision for any specific wastewater reuse activity.

The communication of the results is as important as the results themselves. Without proper communication to the responsible agents or without propagation of the results to other locations, the gathered knowledge cannot generate any improvement. Besides, the information exchange between planning and operative organisations of WWMS in Mexican cities is considered a key success factor in order to increase the quantity and quality of the data for future MFAs in Tepic or any other Mexican city. The more data and information about volume flows and nutrient concentrations is available, the more accurate and realistic the results become and thus an effective support of the urban water system can be possible.

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Annex A - Complementary details

Annex A1 - Calculation of TCs in the Water Supply process.

The calculation of the TCs in the water supply process was based on the water user registry and water fees and based on the information provided by the SIAPA Tepic regarding yearly water abstraction volumes and water losses. The steps followed are explained below and afterwards the list with the variables used for the calculations is included.

Step 1: For each Fee type, the total payable amount was calculated by means of multiplying the number of contracts by the Monthly fee (results in units of MXN$ $month^{-1}$).

Step 2: The total billed fees in the city were calculated by adding the payable amounts for all Fee types (results in units of MXN$ $month^{-1}$).

Step 3: The monthly total groundwater input to the city was calculated by dividing the yearly groundwater abstraction by 12 (results in units of m^3 $month^{-1}$).

Step 4: The drinking water provided to the users in the city was calculated by subtracting the reported water losses from the monthly total groundwater input to the city (results in units of m^3 $month^{-1}$).

Step 5: A fee per unit of volume was calculated by dividing the total billed fees (step 2) by the monthly provided water volume (step 4) (results in units of MXN$ m^{-3}).

Step 6: Under the assumption that the water fees are proportional to the volume of water provided, the volume provided to each Fee type was calculated by dividing the total payable amount calculated in step 1 by the water fee calculated in step 4 (results in m^3 $month^{-1}$).

Step 7: The results of step 6 were grouped according to the user classification in this research to obtain the total volume used by each user category (results in m^3 $month^{-1}$).

Step 8: The TCs for each user category in the process Water Supply were calculated by dividing the volume obtained in step 6 by the monthly total volume of groundwater abstraction (results are unit-less).

For the calculation of the TCs in scenarios 2011 and 2030 it was assumed that the ratios between the volumes consumed by each user category would remain constant changing only the total volumes of groundwater and the rates of water losses in each year.

User classification in 2006 according to SIAPA Tepic and to this research

Fee type	Description according to SIAPA	Type of user (SIAPA)	Contracts	Monthly fee	User category in this research
11	Condominium	Domestic user	1	$4,036	Households
1D	Domestic service (high)	Domestic user	2483	$186	Households
1B	Domestic service (low)	Domestic user	70570	$65	Households
1C	Domestic service (medium)	Domestic user	5471	$145	Households
1A	Empty grounds / Empty house	Domestic user	4560	$35	Households
12B	Housing complex, up to 10 houses (low)	No description	0	$1,080	Households
12A	Housing complex, up to 10 houses (min)	Domestic user	1	$649	Households
12C	Housing complex, up to 10 houses (min)	No description	0	$810	Households
SCM	Measured commercial service	Domestic user	801	$80	Households
SDM	Measured domestic service	Domestic user	1872	$61	Households
2D	Scattered homes (up to 2 houses, high)	Domestic user	36	$479	Households
2B	Scattered homes (up to 2 houses, low)	Domestic user	108	$242	Households
2C	Scattered homes (up to 2 houses, med)	Domestic user	70	$325	Households
2A	Scattered homes (up to 2 houses, min)	Domestic user	334	$163	Households
6	Car washing	Industrial user	17	$777	Industry
34	Laundries	Industrial user	25	$470	Industry
27	Water purification industry	Industrial user	3	$746	Industry
5A	Bank	Public service	669	$857	NI Use
4C	Bar with toilet (no shower)	Tourism and commercial user	17	$332	NI Use
17	Brick and tiles fabric	Commercial user (products + services)	1	$650	NI Use
32C	Bus station large	Public service	2	$3,570	NI Use
32B	Bus station medium	Public service	1	$1,692	NI Use
32A	Bus station small	Public service	2	$688	NI Use

20	Clinic	No description	0	$813	NI Use
15B	Commercial establishments (more than 15)	Commercial user (products + services)	1	$13,580	NI Use
15A	Commercial establishments (up to 15)	Commercial user (products + services)	2	$4,036	NI Use
21	Department stores	Commercial user (products + services)	7	$398	NI Use
22	Funerary services	Commercial user (products + services)	8	$442	NI Use
33	Gym/Church/Plant nursery	Commercial user (products + services)	60	$566	NI Use
9A	Hotel 1 star	Tourism and commercial user	10	$2,825	NI Use
9B	Hotel 2 stars	Tourism and commercial user	4	$3,570	NI Use
9C	Hotel 3 stars	Tourism and commercial user	2	$4,440	NI Use
9D	Hotel 4 stars	Tourism and commercial user	3	$5,246	NI Use
10	Motel	Commercial user (products + services)	6	$2,142	NI Use
23	Cinema	Tourism and commercial user	4	$470	NI Use
4D	Night club	No description	0	$679	NI Use
16B	Offices (more than 5)	Public service	1	$2,142	NI Use
16A	Offices (more than 5)	Public service	4	$392	NI Use
29	Party local	Tourism and commercial user	6	$566	NI Use
4B	Restaurant/lodging	No description	0	$813	NI Use
4A	Small fast food / tacos	Commercial user (products + services)	1091	$201	NI Use
3A	Small grocery stores	Commercial user (products + services)	4837	$114	NI Use
14D	Sports club	Tourism and commercial user	2	$2,211	NI Use
8	Sports club	Tourism and commercial user	1	$5,143	NI Use
37	Train services	Public service	1	$2,825	NI Use

Monthly fee in MXN$. Source: Castillo Delgado 2007.

Annex A2 - Calculation of the Transfer Coefficient for House Roof Inflow

The transfer coefficient *Rain to Sealed Areas* → *House Roof Inflow* ($TC_{HR-Inflow}$, necessary in sub-process Sealed Areas, Figure 4.6), determines the amount of stormwater flowing from the sealed areas towards the WW Sewer through domestic connections. It was calculated in this research based on expert consultation, literature research and on the study of satellite images of the city. Following formula was applied:

$$TC_{HR-Inflow} = A_{House} \cdot A_{House,WWSewer}$$

Where A_{House} represents the share of the sealed area in the city corresponding to houses and $A_{House,WWSewer}$ represents the share of the houses in the city whose roofs and yards are connected to the WW Sewer. The table below presents the information used for the calculations and as well as the results obtained.

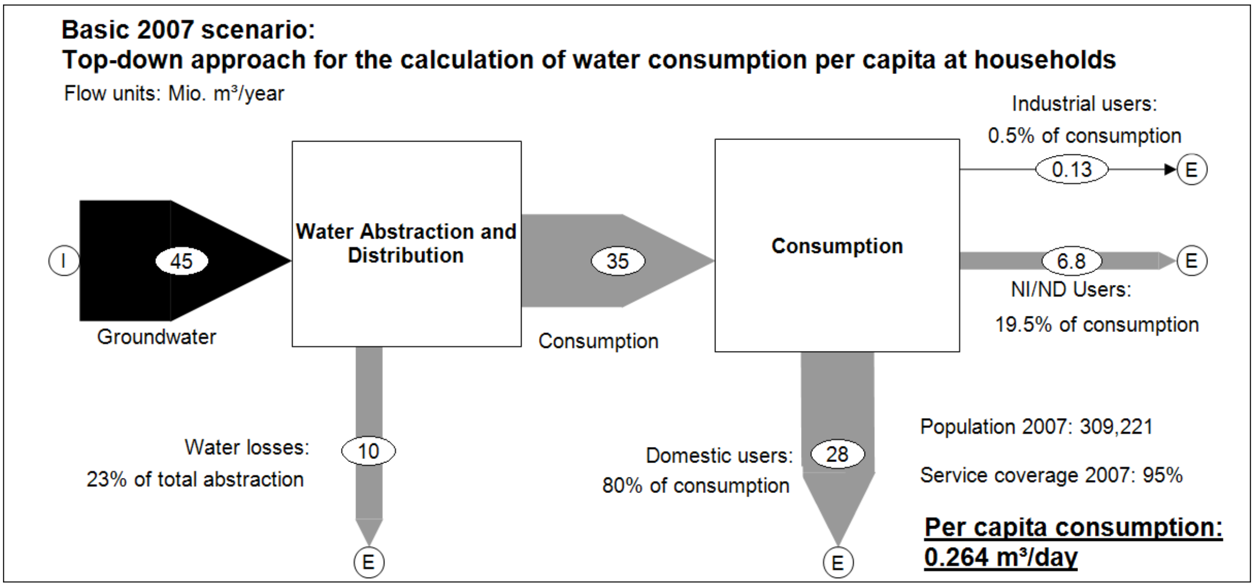
Calculation of the Transfer Coefficient for House Roof Inflow

Scenario	A_{House}	$A_{House,WWSewer}$	$TC_{HR-Inflow}$
2007	0.50^{a}	0.25^{b}	0.125
2011	0.50^{a}	0.25^{b}	0.125
2030	0.50^{a}	0.20^{b}	0.100

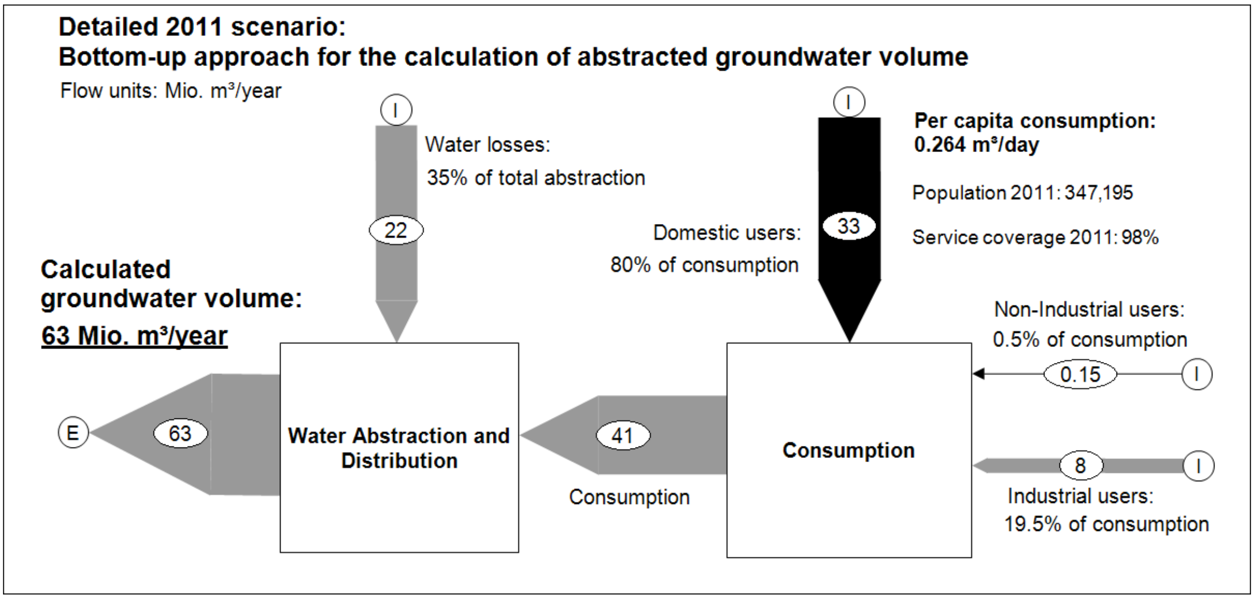
[a] Information source: Martinez et al. 2011, Bardou 2012, satellite images of the city.
[b] Information source: obtained under expert in collaboration with experts from SIAPA Tepic and from the city council. The reduction of the $A_{House,WWSewer}$ value for the 2030 scenario is given by the decrease in the connection degree of households to the WW Sewer as described in Table 3.2

Annex A3 - Calculation of water consumption per capita at Household

The water consumption per capita in the basic scenarios 2007 and 2011 was calculated using a top-down approach based on the groundwater abstraction values, on the reported water losses in the drinking water system and on the consumption distribution in the city. The figure below illustrates this approach.



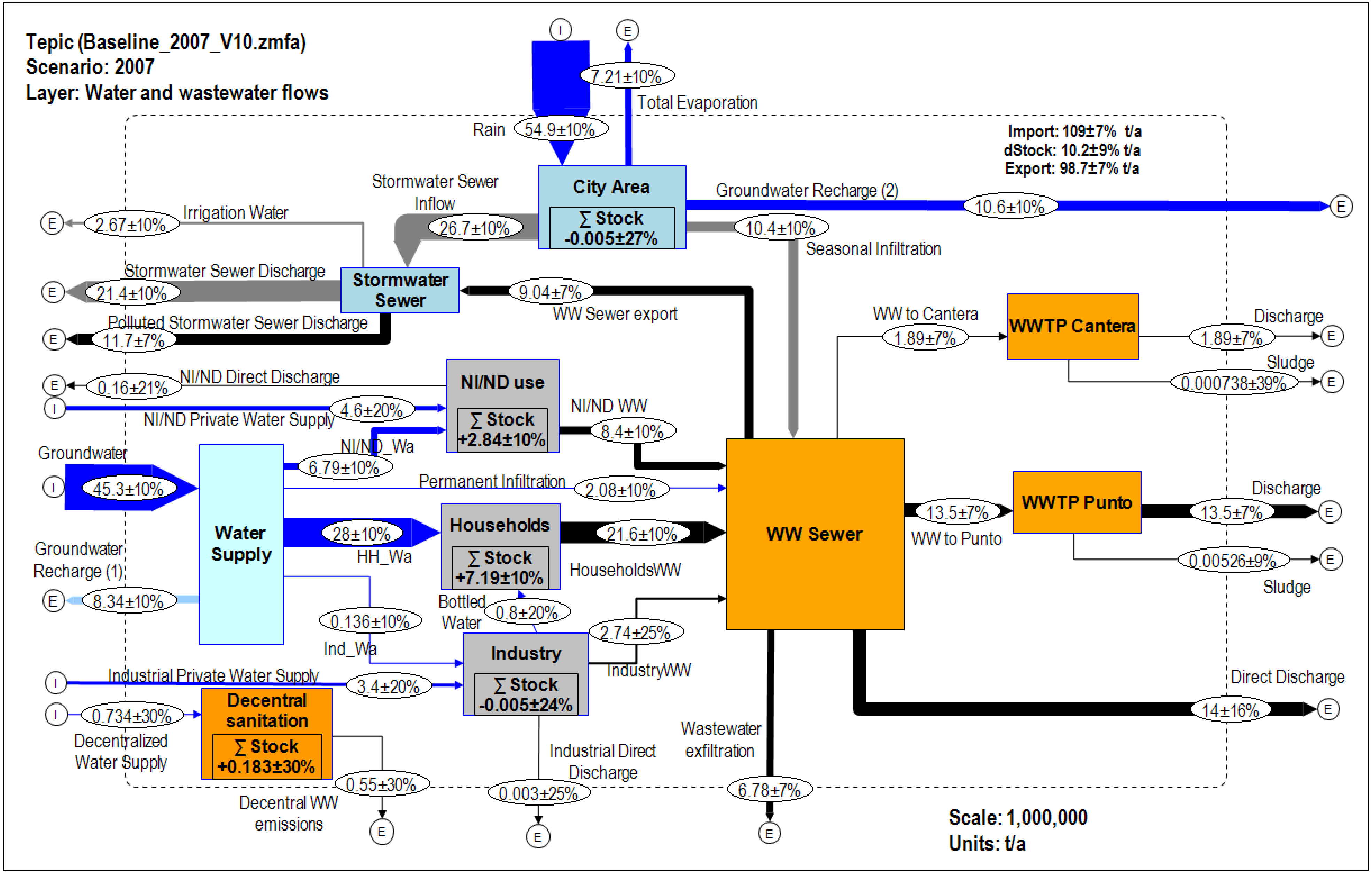
The calculated per capita water volume was used in a bottom-up approach to calculate the projected groundwater abstraction in the detailed 2011 and 2030 scenario. The figure below illustrates this approach.



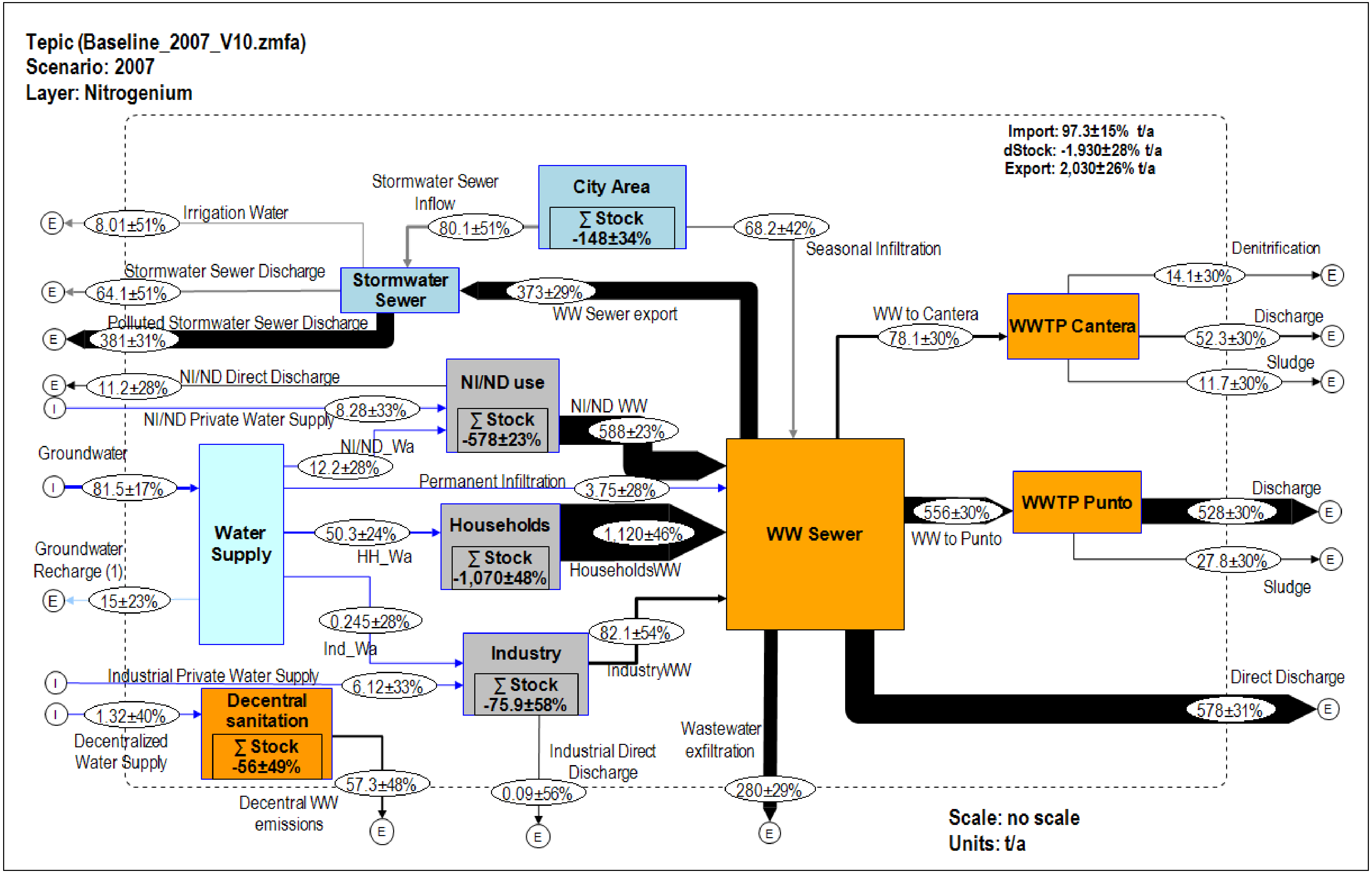
Annex A4 - Results of the basic scenarios 2007, 2011 and 2030

Unless something different is indicated, following indications apply:

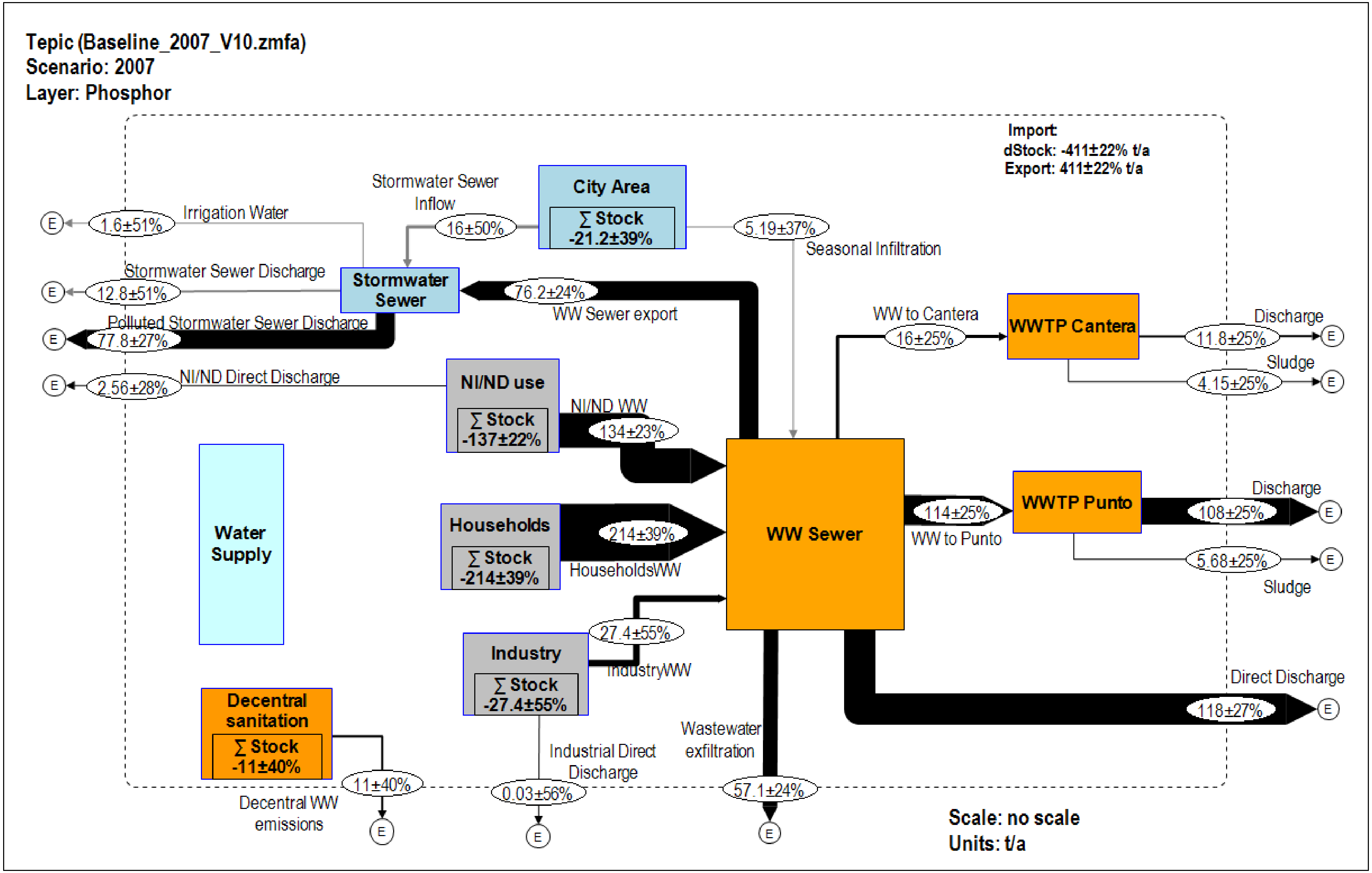
- Mass flows rounded to 3 significant digits.
- The calculated uncertainty for each flow is displayed next to the flow value.
- Flows with an average value of zero are hidden.
- "Σ Stock" standing alone indicates a stock with an average value of zero.
- Abbreviations: E=Export, HH= Households, I=Import, Ind=Industrial, NI/ND=Non-Industrial/Non-Domestic, Wa= Drinking Water, WWTP= Wastewater Treatment Plant, WW=Wastewater.



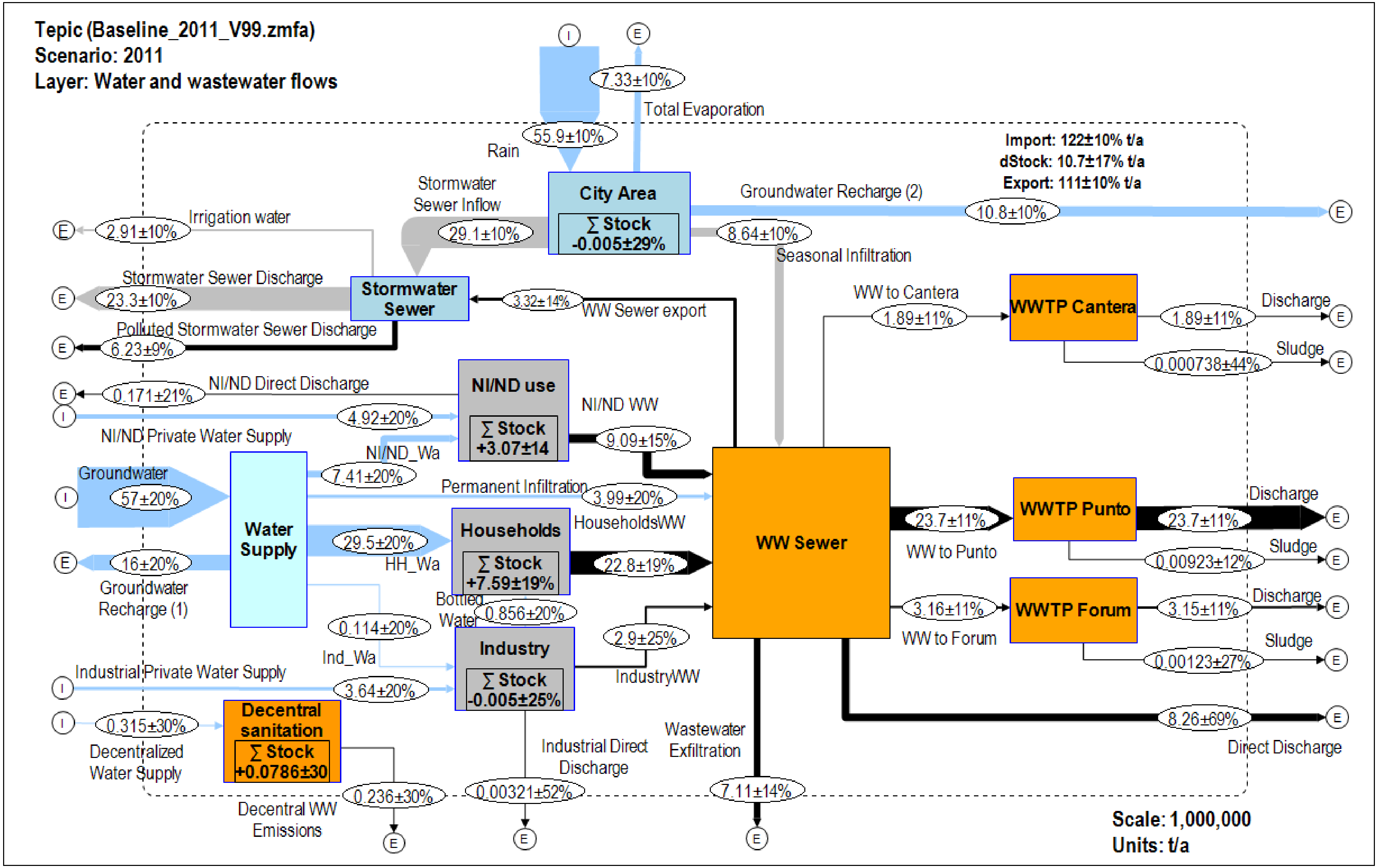
MFA Results: Water and Wastewater flows. Scenario 2007



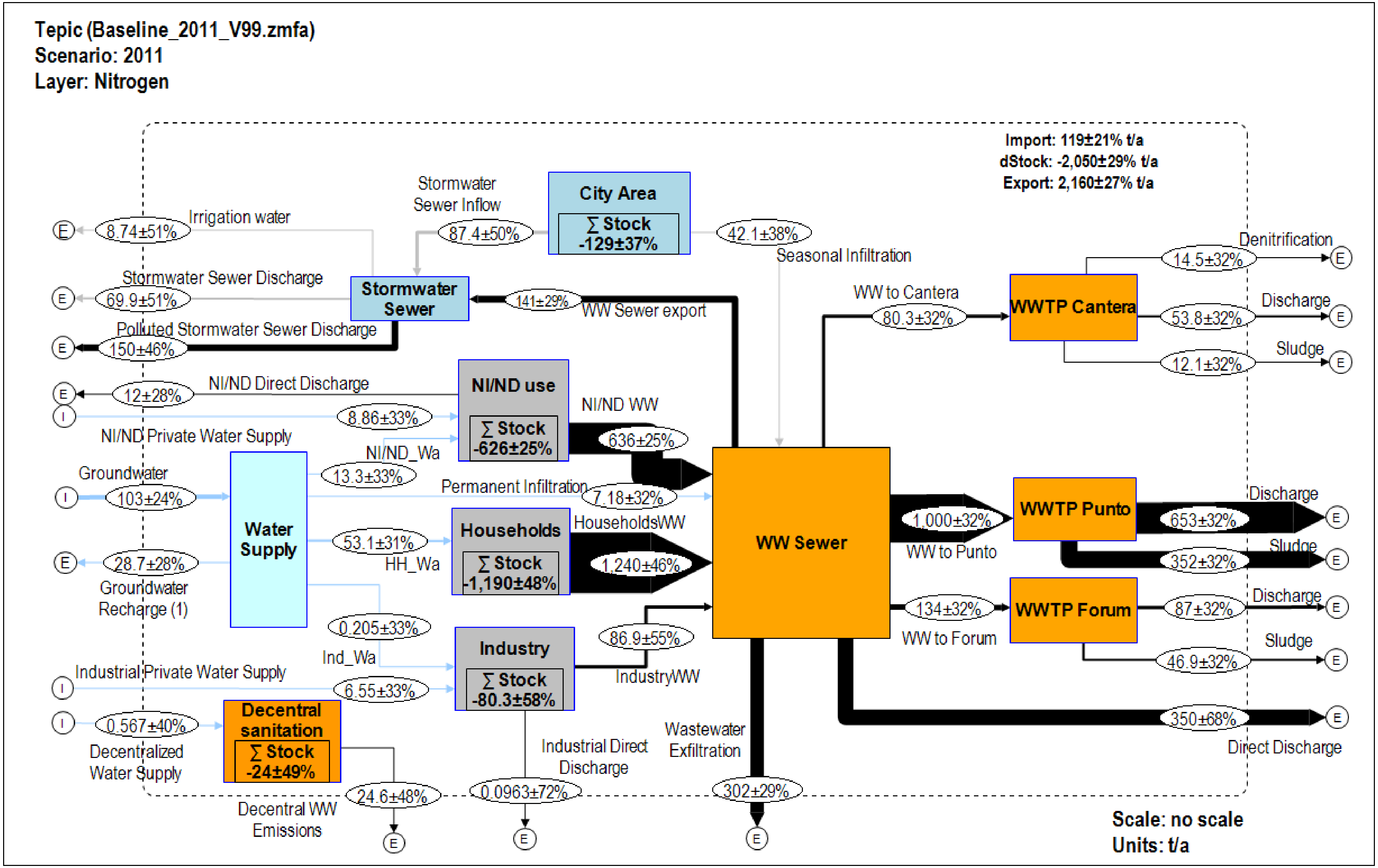
MFA Results: Nitrogen layer. Scenario 2007



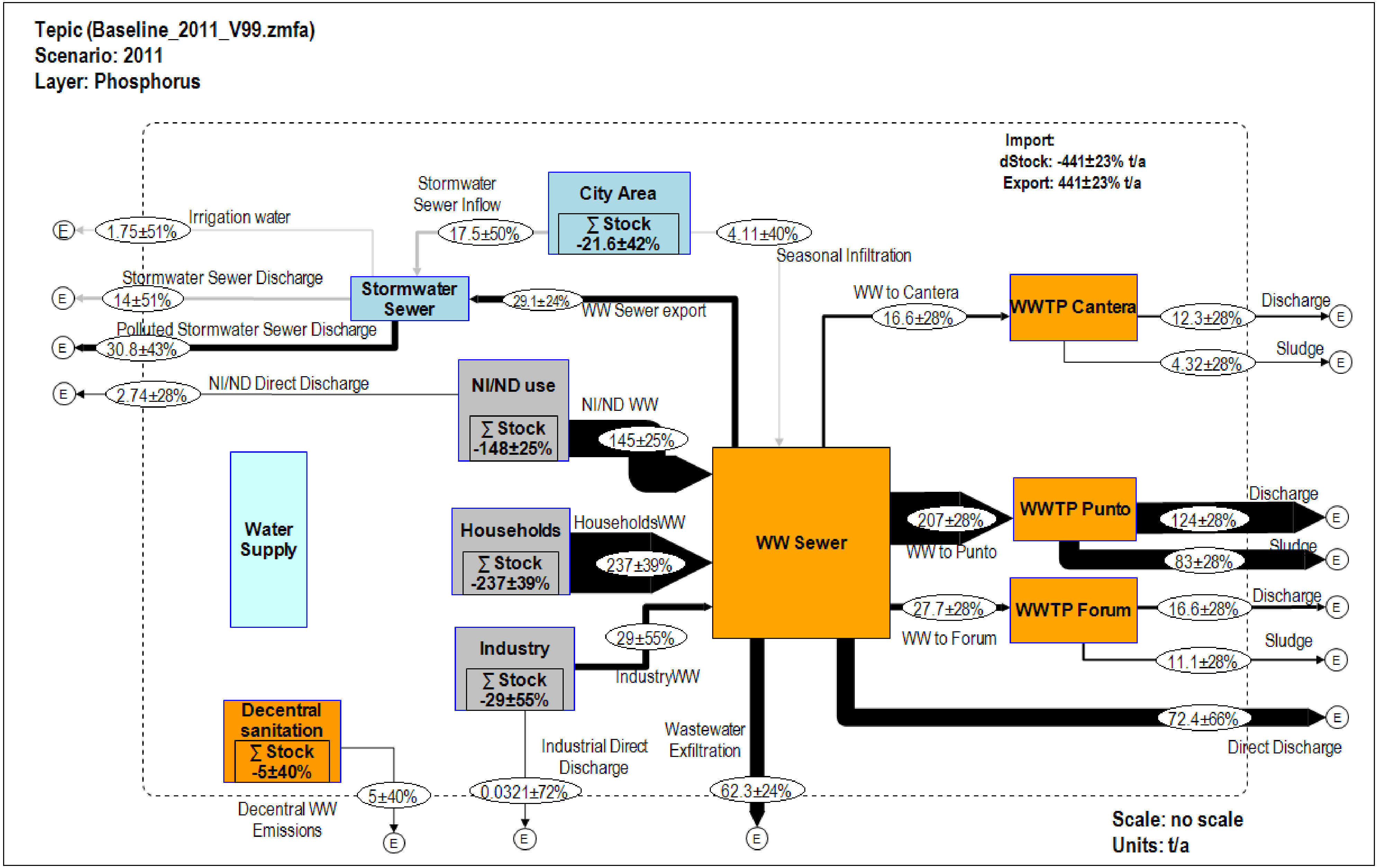
MFA Results: Phosphorus layer. Scenario 2007.



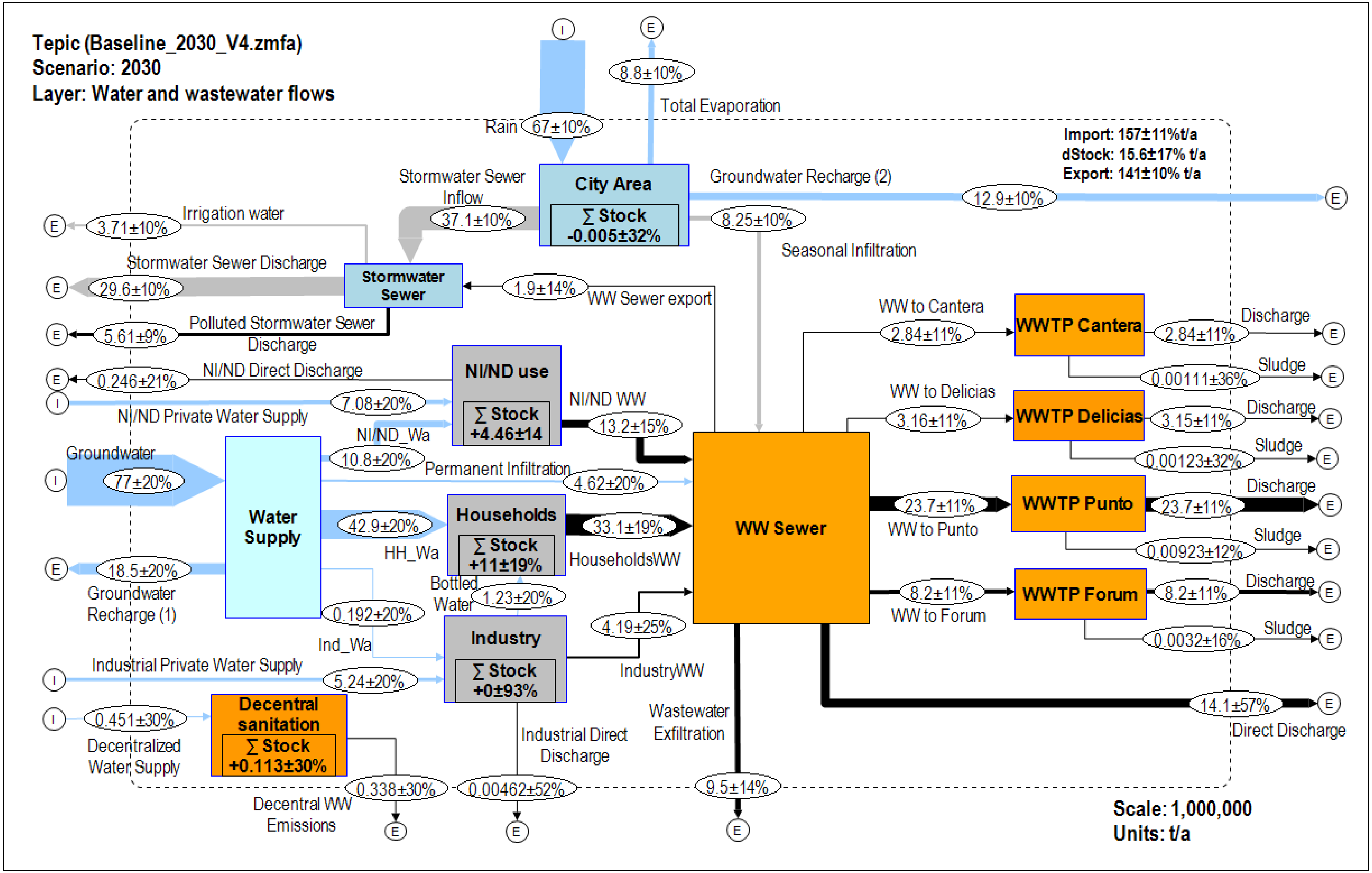
MFA Results: Water and Wastewater flows. Scenario 2011



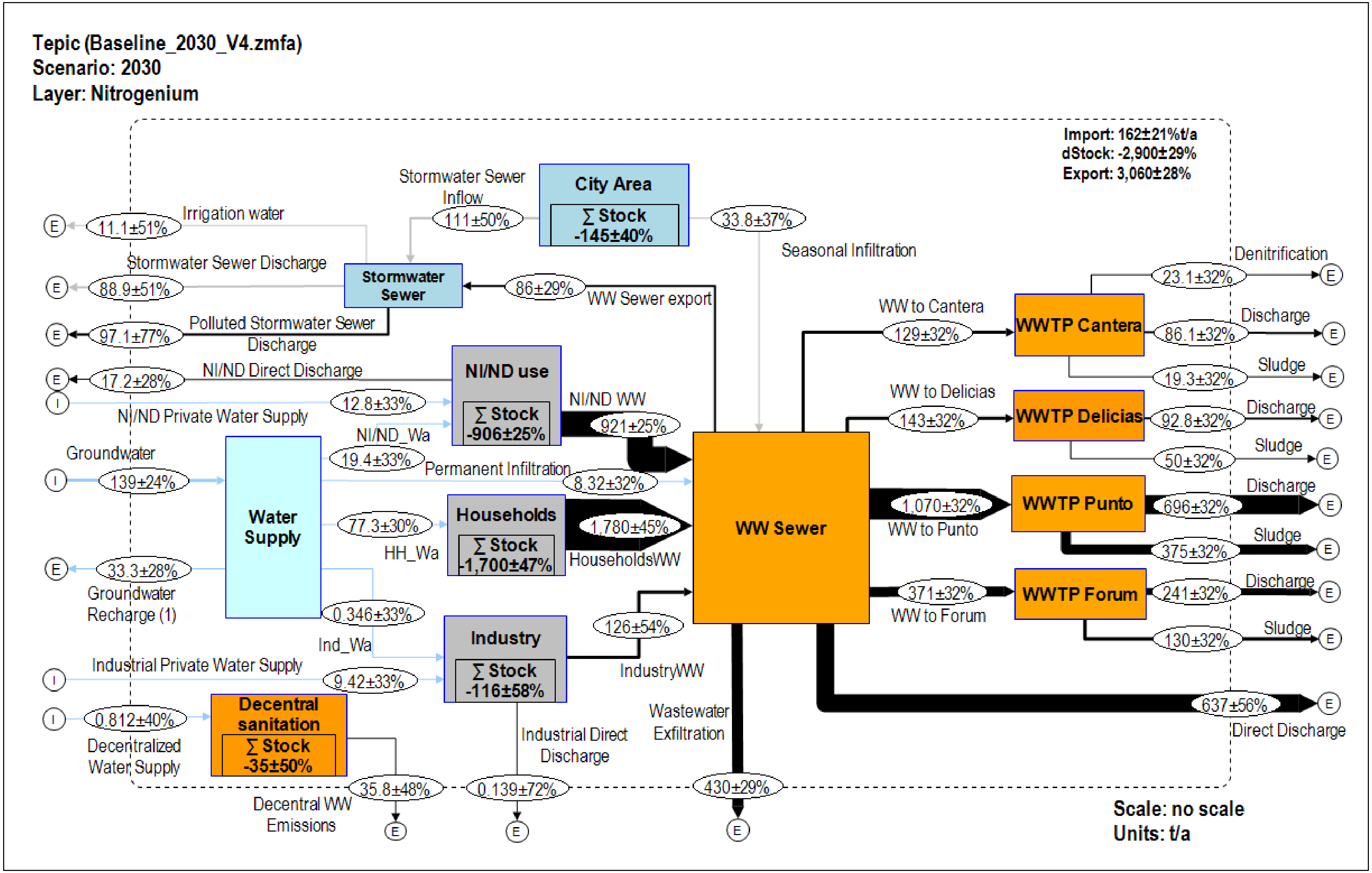
MFA Results: Nitrogen layer. Scenario 2011



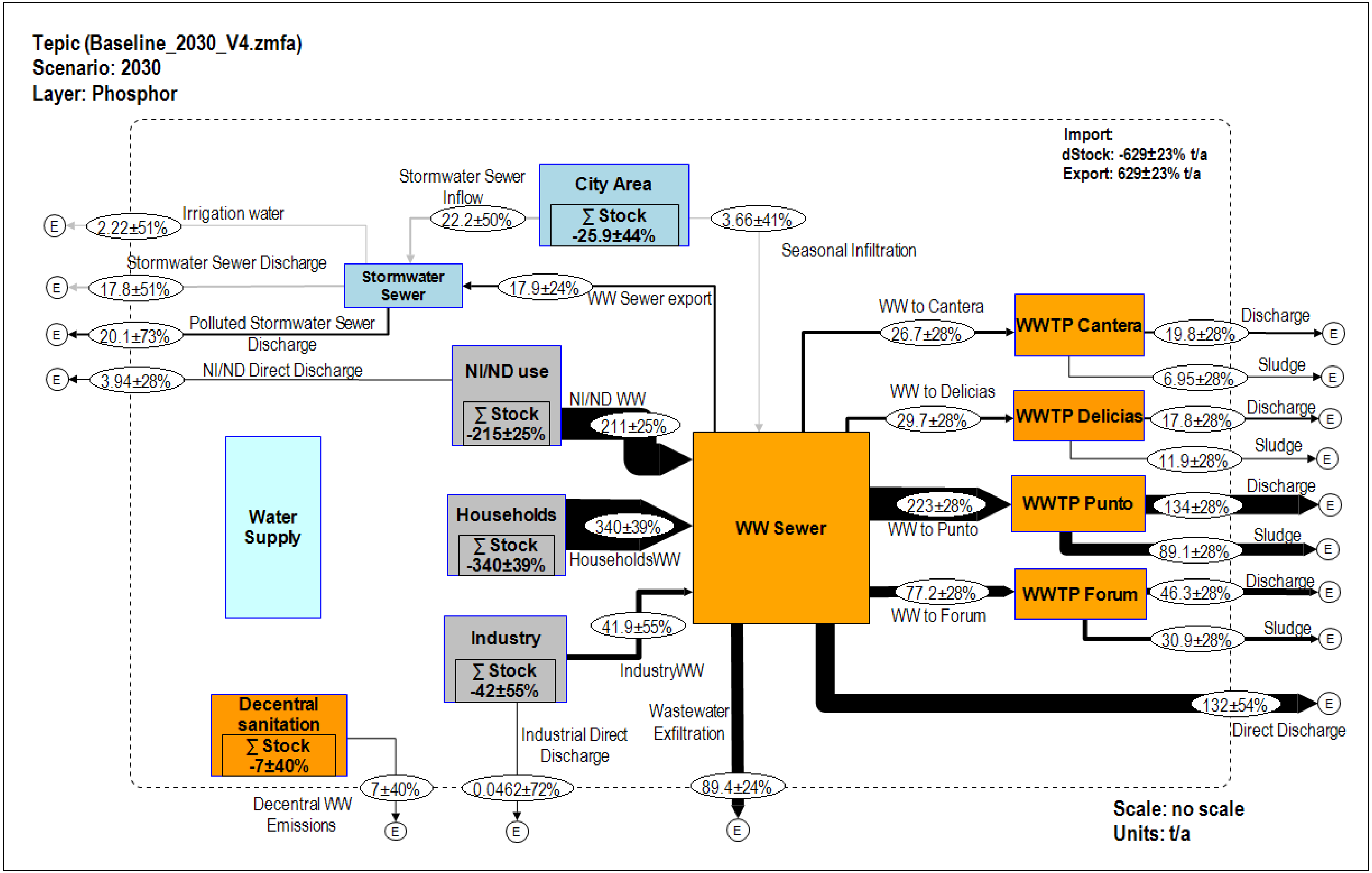
MFA Results: Phosphorus layer. Scenario 2011



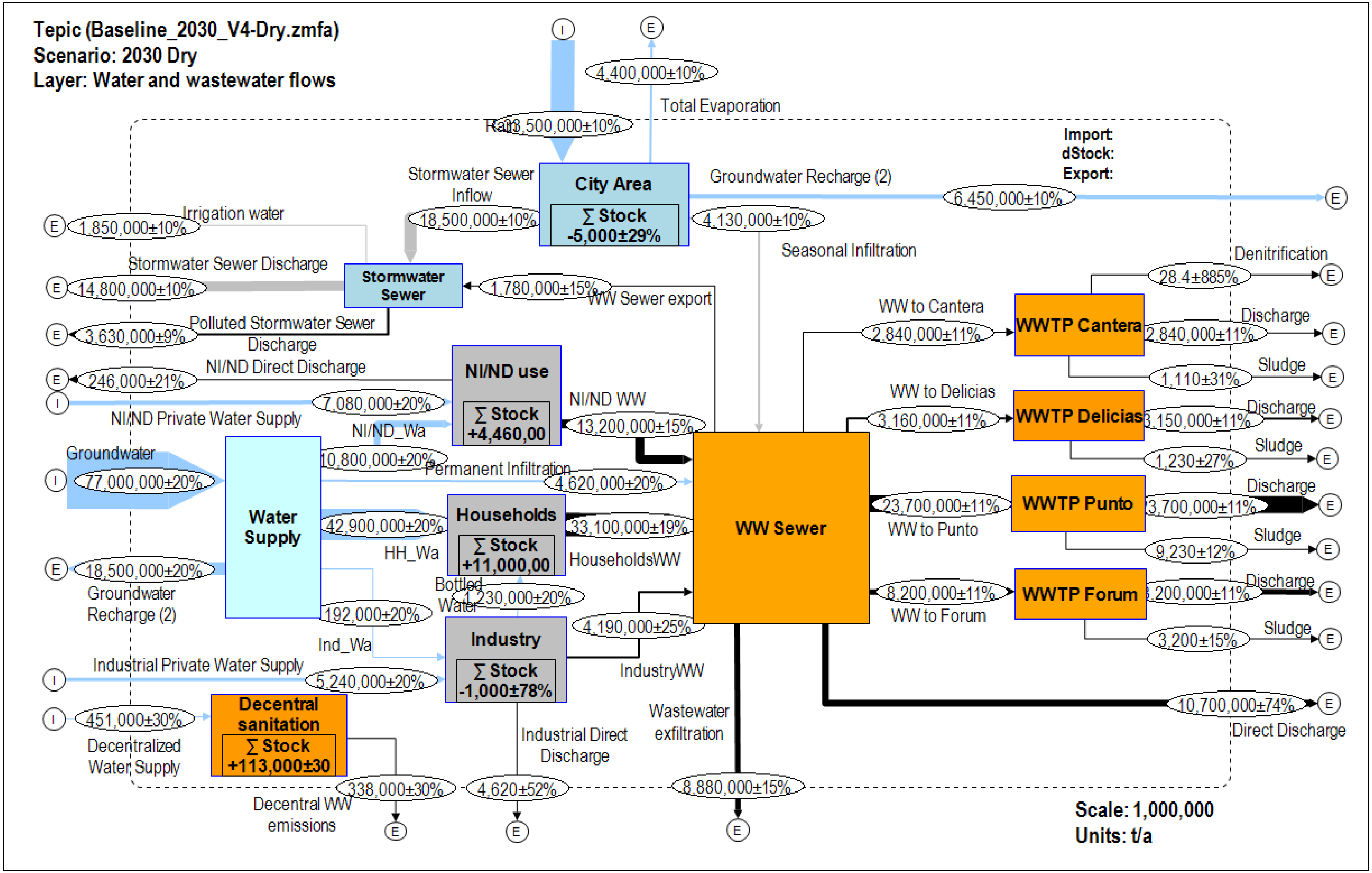
MFA Results: Water and Wastewater flows. Scenario 2030



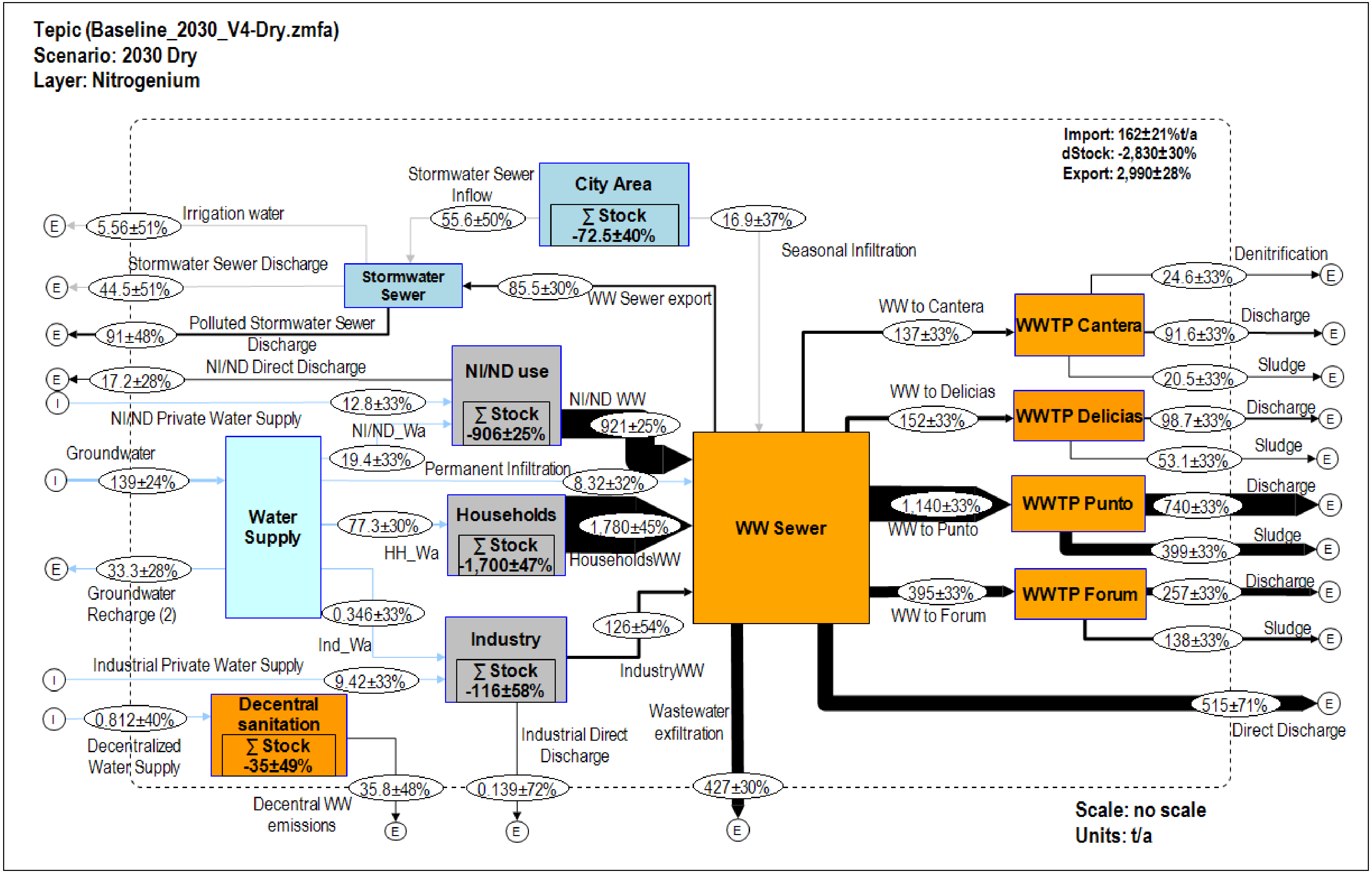
MFA Results: Nitrogen layer. Scenario 2030



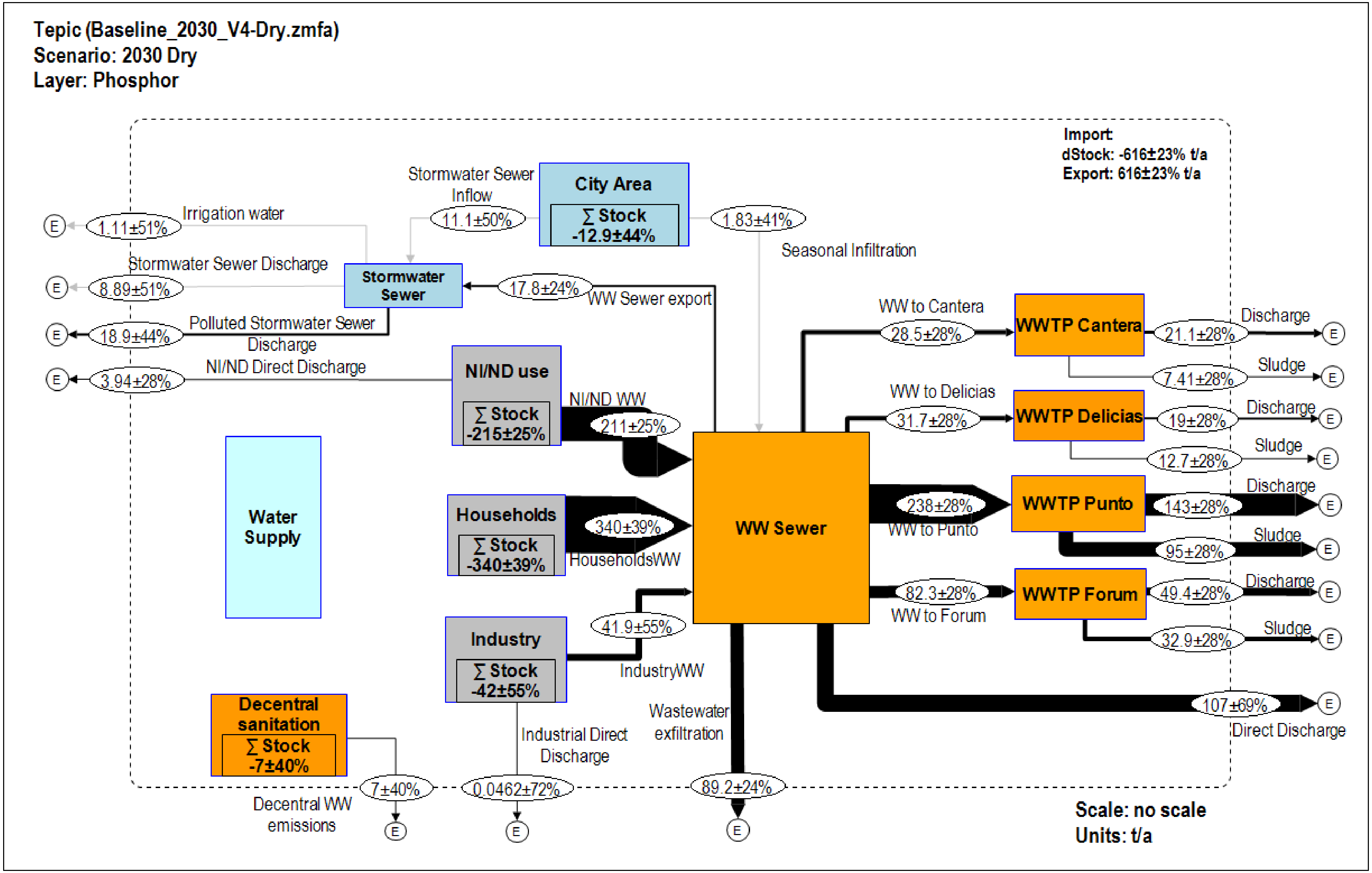
MFA Results: Phosphorus layer. Scenario 2030



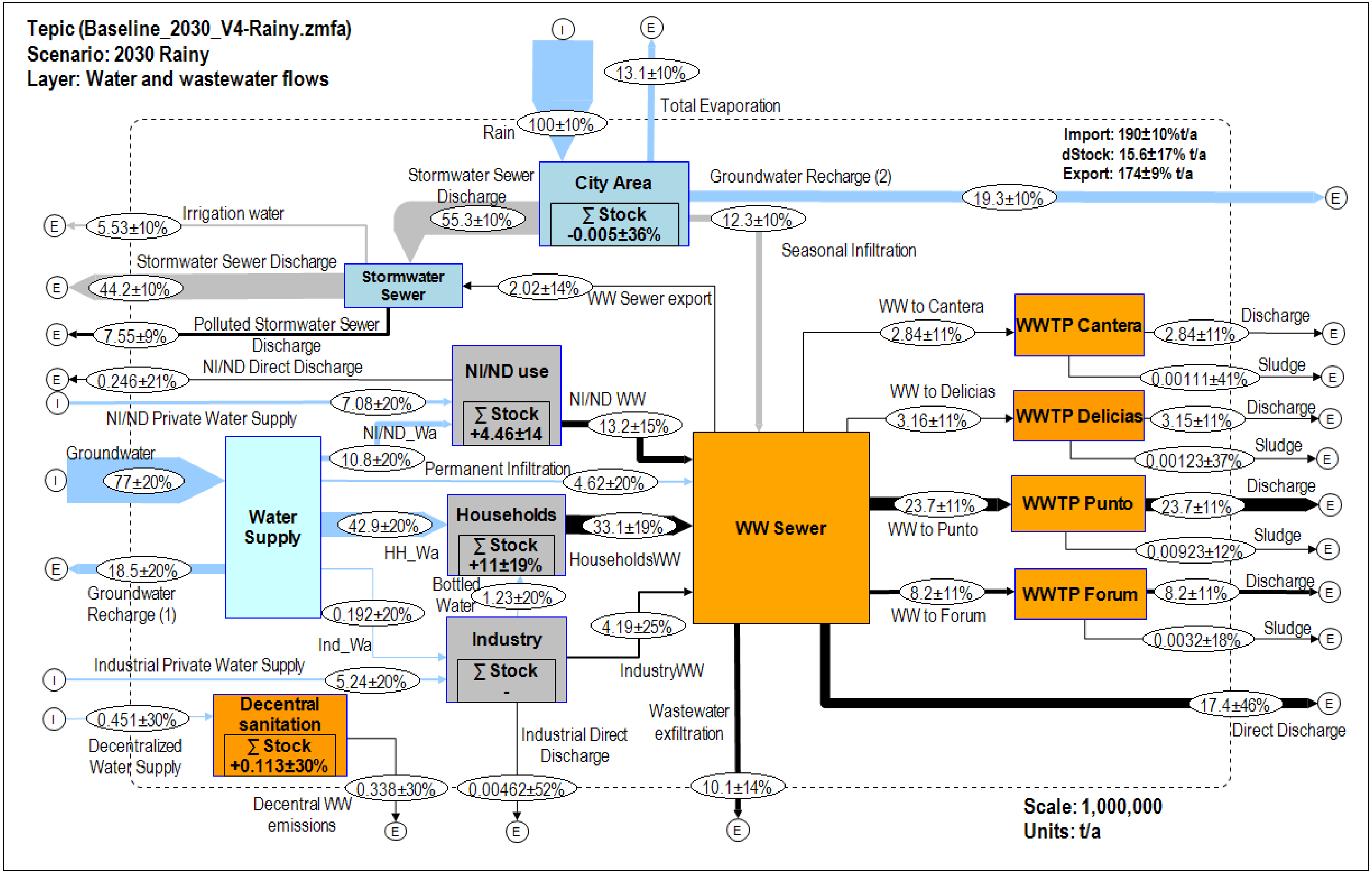
MFA Results: Water and Wastewater flows. Scenario 2030 Dry



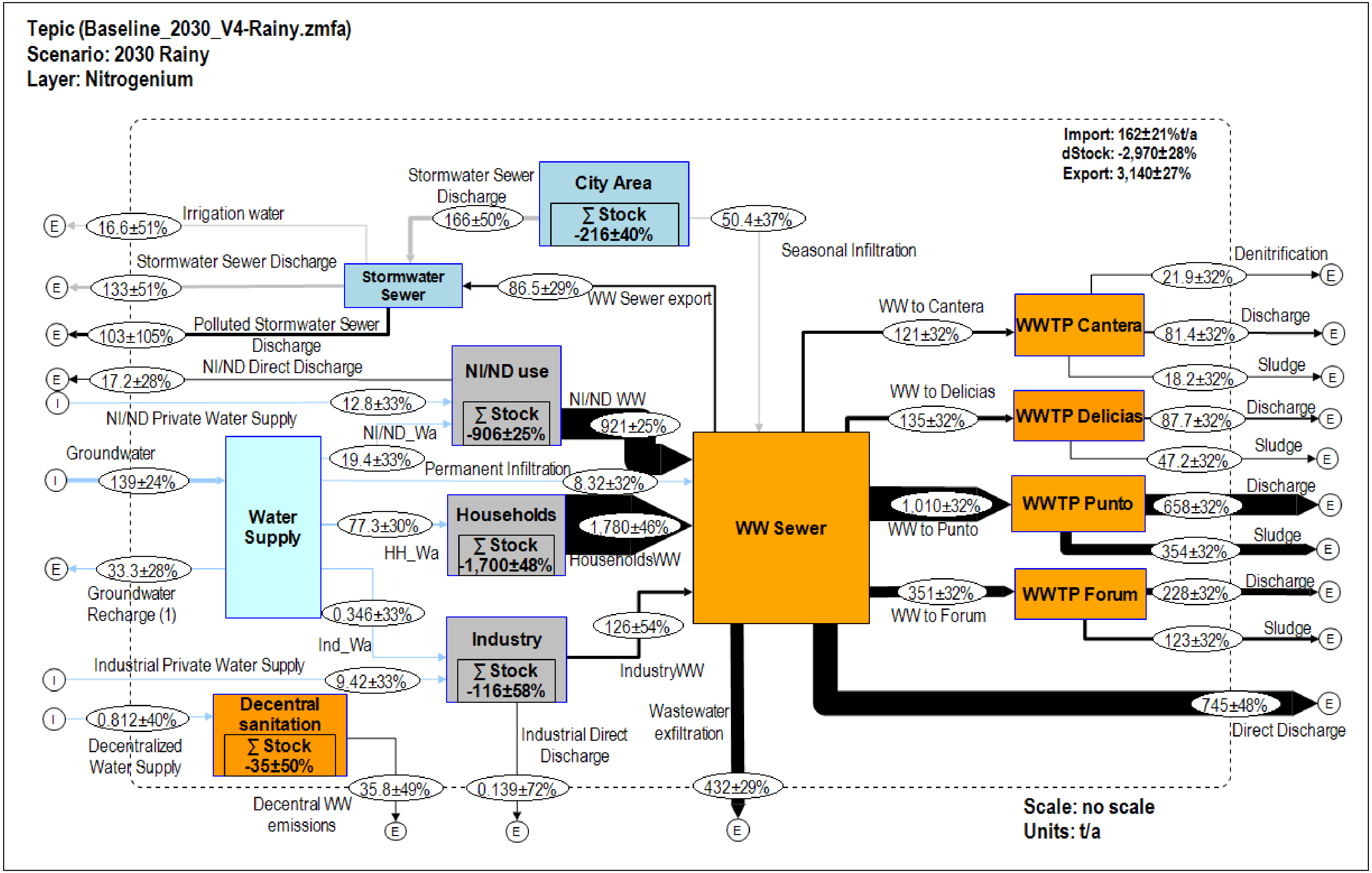
MFA Results: Nitrogen layer. Scenario 2030 Dry



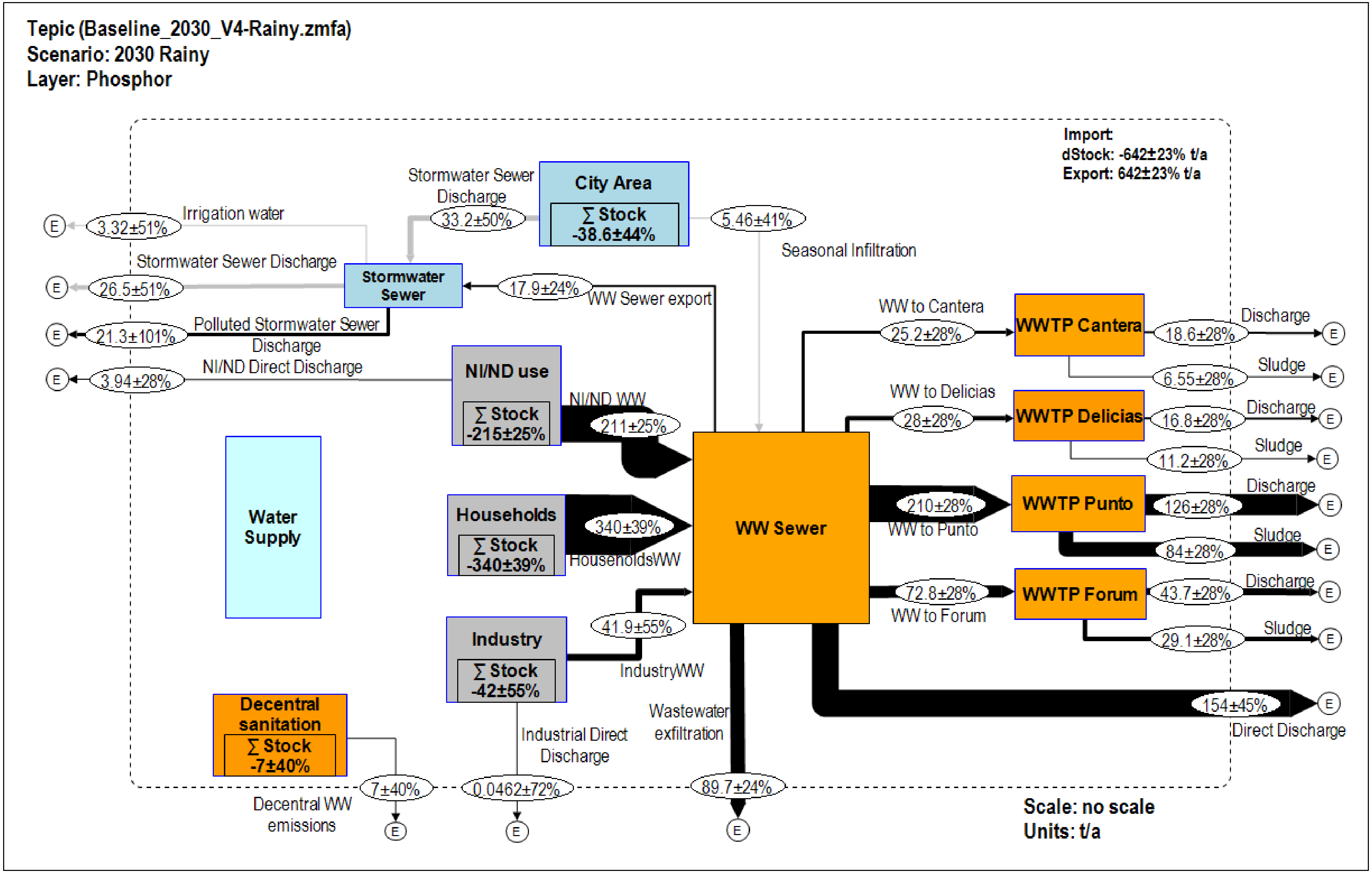
MFA Results: Phosphorus layer. Scenario 2030 Dry



MFA Results: Water and Wastewater flows. Scenario 2030 Rainy



MFA Results: Nitrogen layer. Scenario 2030 Rainy

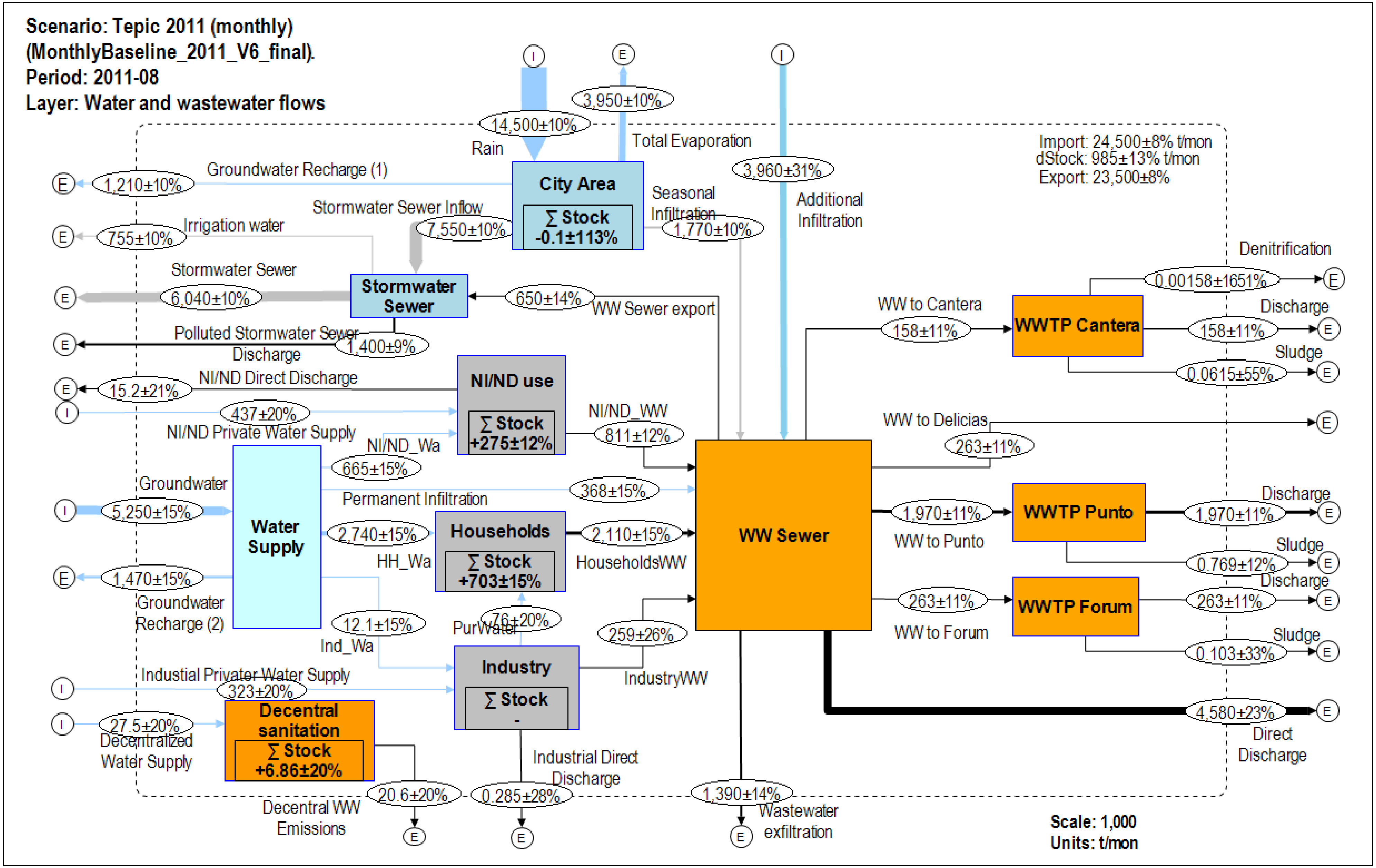


MFA Results: Phosphorus layer. Scenario 2030 Rainy

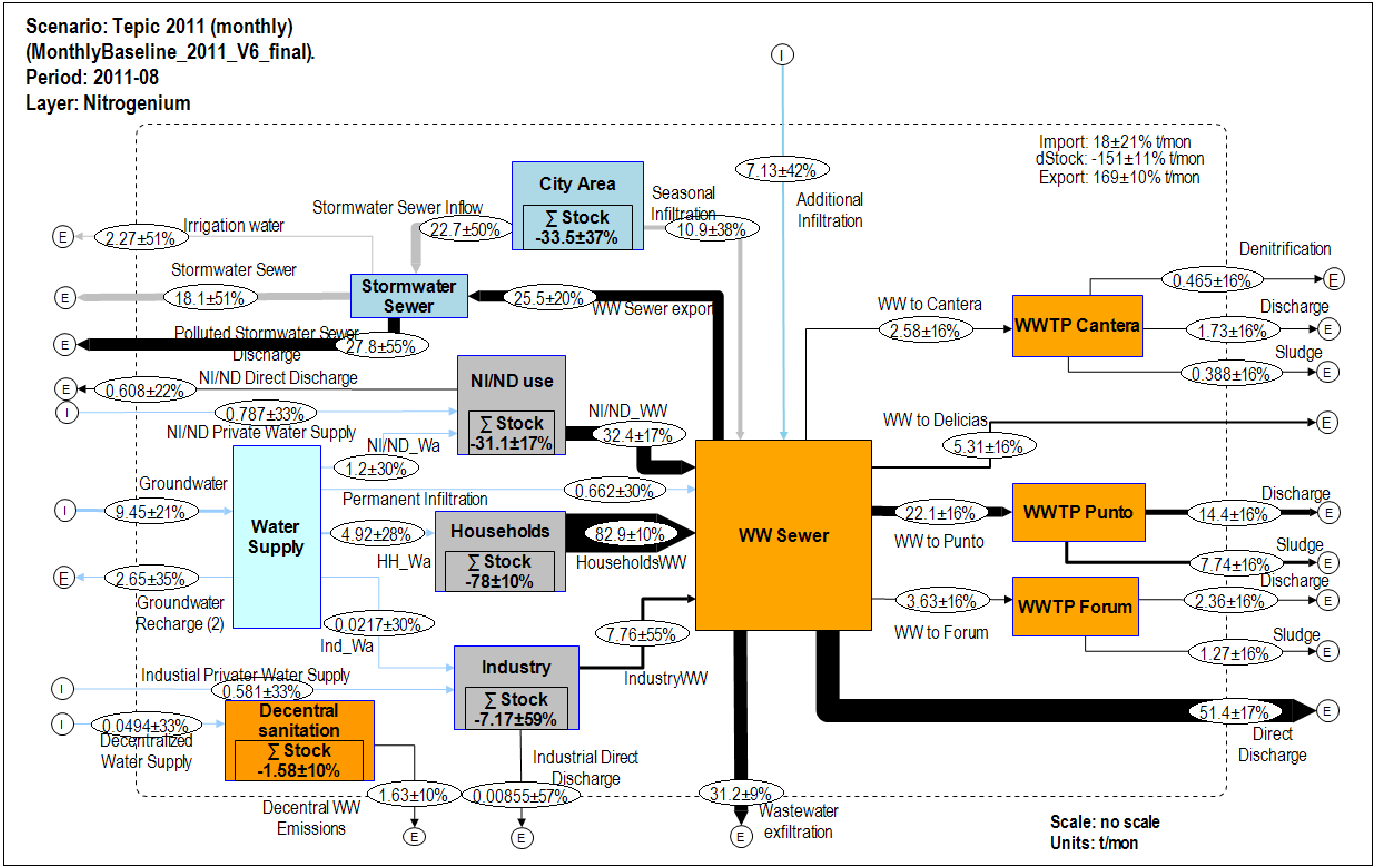
Annex A5 - Results of the detailed scenario 2011 (August and dry season)

Unless something different is indicated, following indications apply:

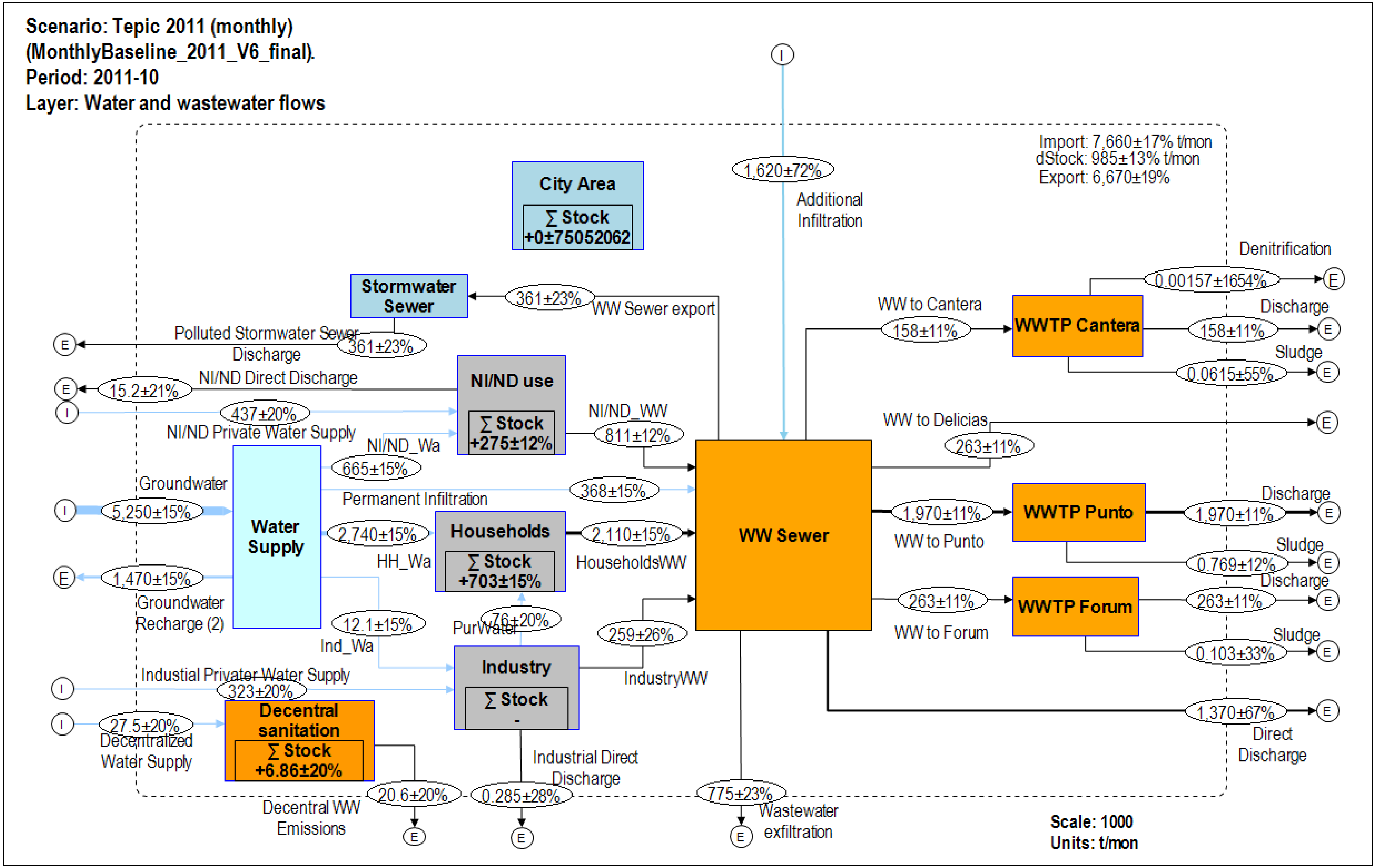
- Mass flows rounded to 3 significant digits.
- The calculated uncertainty for each flow is displayed next to the flow value.
- Flows with an average value of zero are hidden.
- "Σ Stock" standing alone indicates a stock with an average value of zero.
- Abbreviations: AWI: Additional Water Input, E=Export, HH= Households, I=Import, Ind=Industrial, NI/ND=Non-Industrial/Non-Domestic, Wa=Drinking Water, WWTP=Wastewater Treatment Plant, WW=Wastewater.



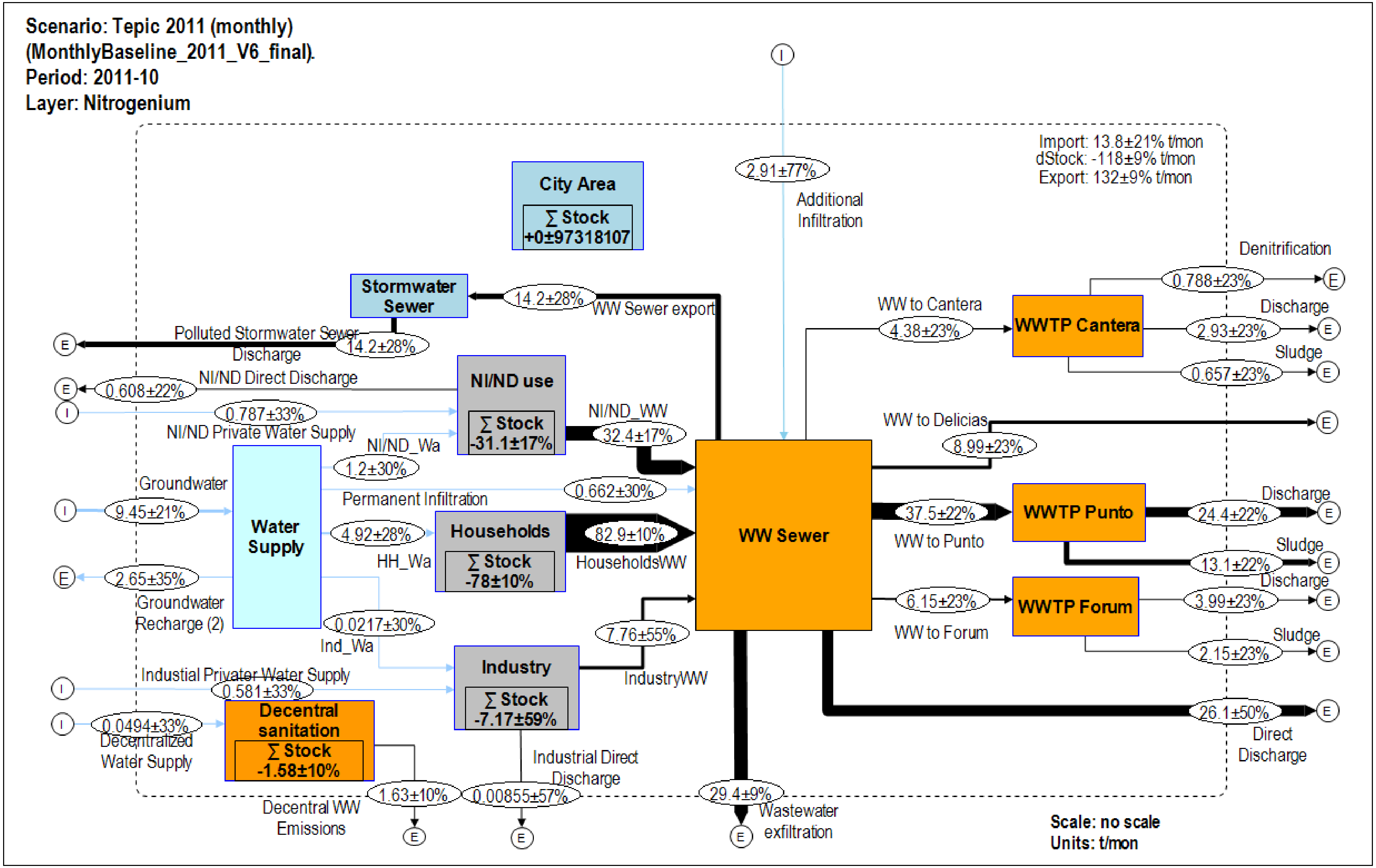
MFA Results: Water and Wastewater flows. Detailed scenario 2011: august



MFA Results: Nitrogen layer. Detailed scenario 2011: august



MFA Results: Water and Wastewater flows. Detailed scenario 2011: october

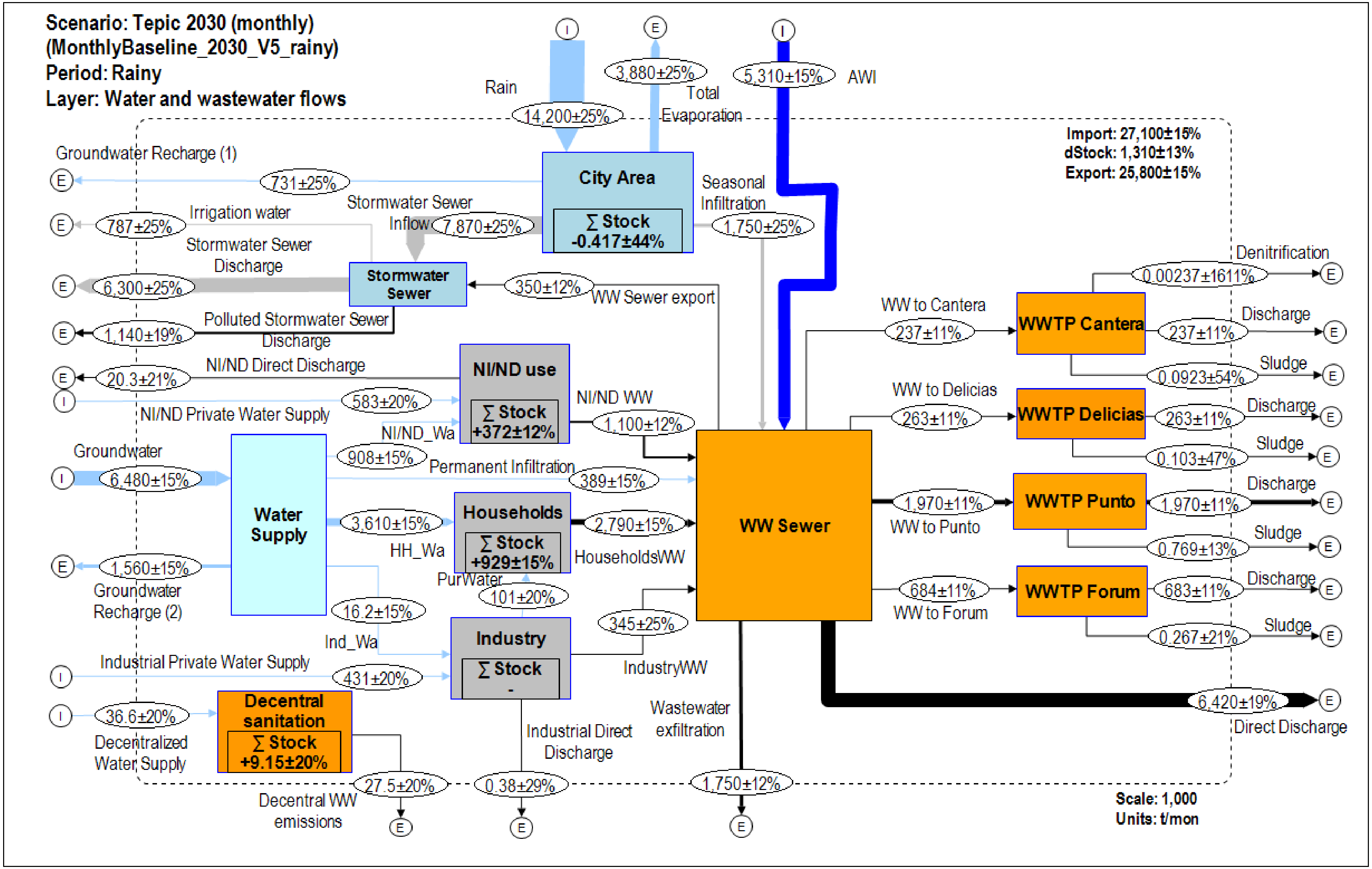


MFA Results: Nitrogen layer. Detailed scenario 2011: october

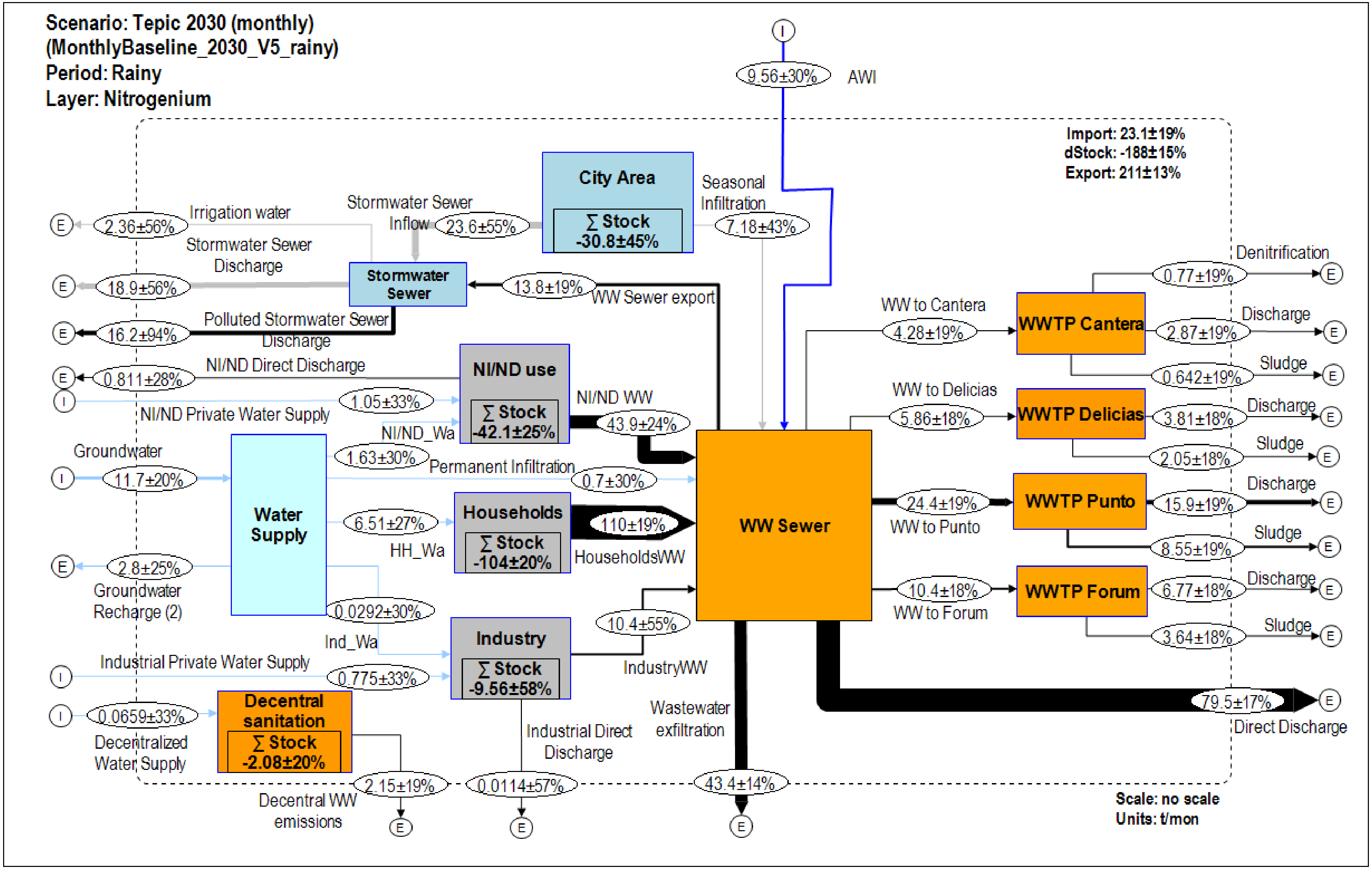
Annex A6 - Results of the detailed scenario 2030 (rainy and dry season)

Unless something different is indicated, following indications apply:

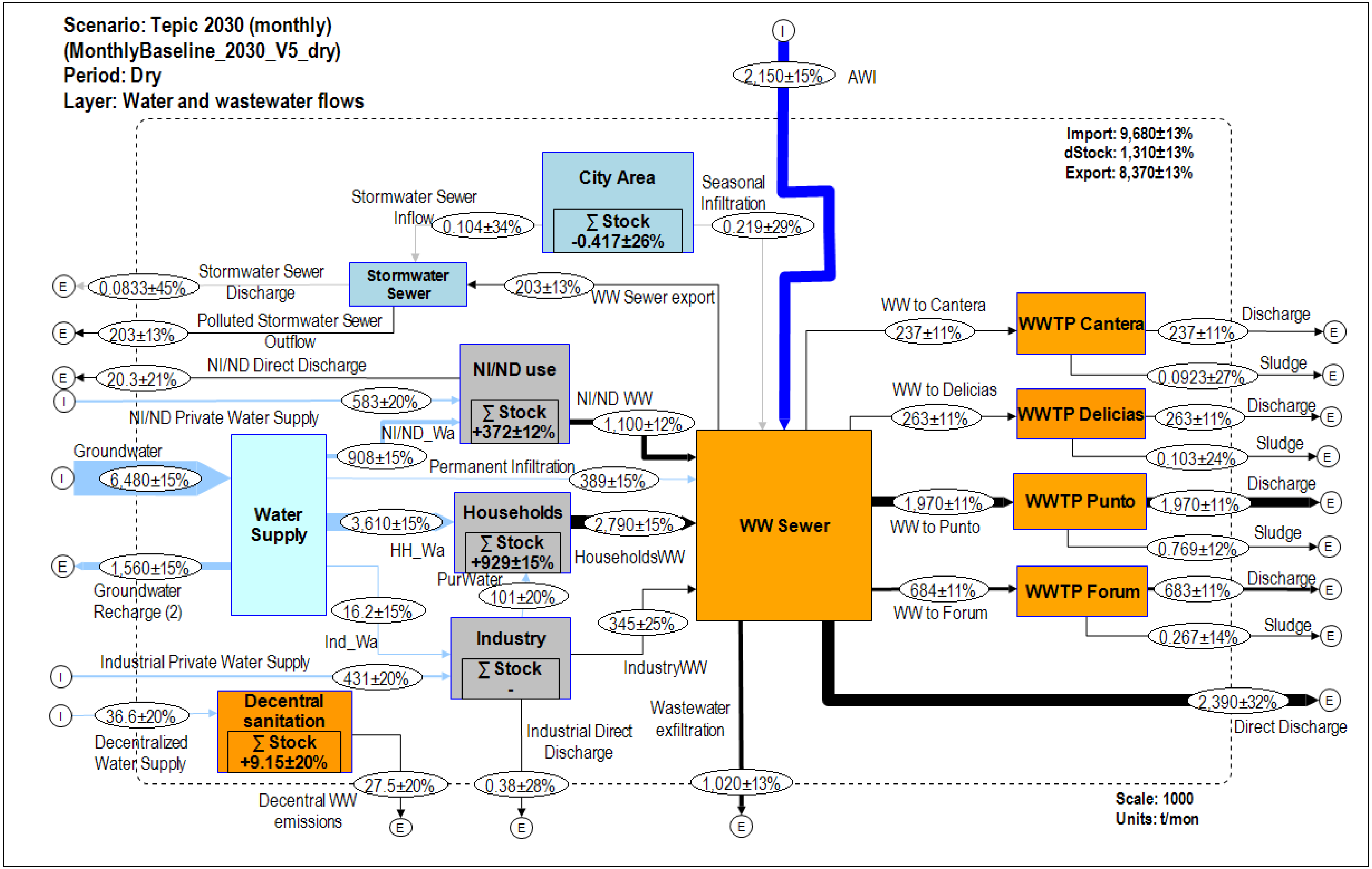
- Mass flows rounded to 3 significant digits.
- The calculated uncertainty for each flow is displayed next to the flow value.
- Flows with an average value of zero are hidden.
- "Σ Stock" standing alone indicates a stock with an average value of zero.
- Abbreviations: AWI: Additional Water Input, E=Export, HH=Households, I=Import, Ind=Industrial, NI/ND=Non-Industrial/Non-Domestic, Wa=Drinking Water, WWTP=Wastewater Treatment Plant, WW=Wastewater.



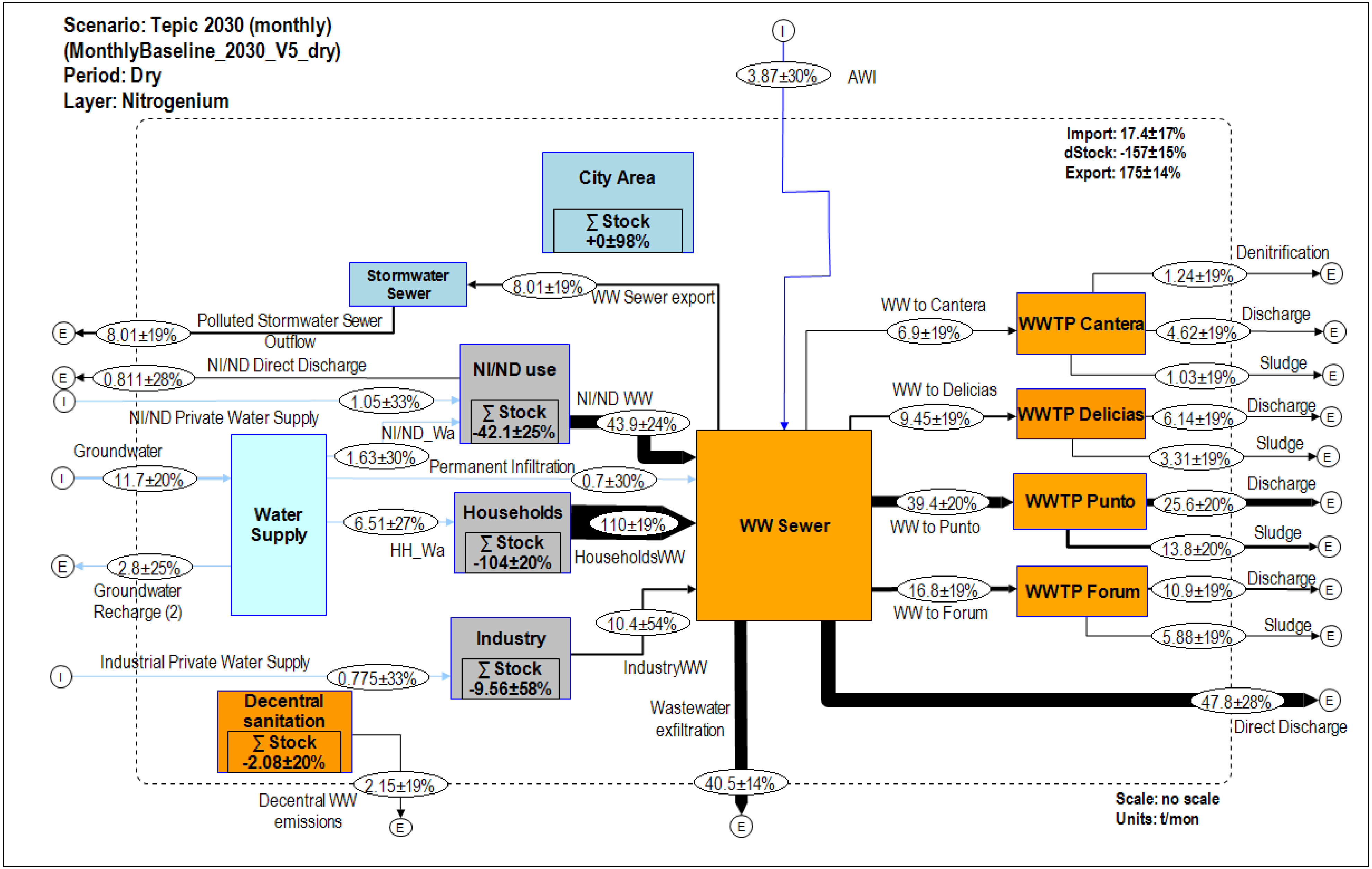
MFA Results: Water and Wastewater flows. Detailed scenario 2030: rainy season



MFA Results: Nitrogen layer. Detailed scenario 2030: rainy season



MFA Results: Water and Wastewater flows. Detailed scenario 2030: dry season



MFA Results: Nitrogen layer. Detailed scenario 2030: dry season

Annex A7 - Results of the sensitivity analysis

The sensitivity analysis was carried out based on the detailed scenario 2030. All original values cited in the tables refer to the value for this scenario and are in units of tonnes month^{-1}.

Evaluation Criteria 1: total groundwater abstraction

Original value (valid for rainy and dry season): **7,533,291**

Parameter changed in +10%	New value	Change
Population number*	8,052,295	6.89%
Water losses	7,822,880	3.84%
NI_Wa	7,717,153	2.44%
Ind_wa	7,577,986	0.59%

*same results as a 10% increase in per capita consumption.

Evaluation Criteria 2: discharge of untreated wastewater

RAINY SEASON, original value **8,575,143**

Parameter changed in +10%	New value	Difference	Change
Utilisation degree	9,496,496	921,353	10.74%
Population*	9,432,200	857,057	9.99%
Total Infiltration	9,274,599	699,457	8.16%
Rain (not sure to use it)	8,750,437	175,294	2.04%
NI_Wa	8,726,171	151,029	1.76%
Water losses	8,666,069	90,926	1.06%
Ind_wa	8,653,213	78,071	0.91%
Treatment capacity at WWTPs	8,259,573	–315,569	–3.68%

DRY SEASON, original value **3,661,449**

Parameter changed in +10%	New value	Difference	Change
Utilisation degreee	4,266,774	605,325	16.53%
Population*	4,189,042	527,593	14.41%
Total Infiltration	3,915,247	253,798	6.93%
NI_Wa	3,792,273	130,824	3.57%
Water losses	3,732,355	70,906	1.94%
Ind_wa	3,719,444	57,994	1.58%
Treatment capacity at WWTPs	3,345,880	–315,569	–8.62%

*same results as a 10% increase in per capita consumption.

Evaluation Criteria 3: Nitrogen export in untreated and treated form

RAINY SEASON

UNTREATED N			TREATED N		
Original value	163.4		Original value	45.0	
Parameter changed in +10%	**New value**	**Change**	**Parameter changed in +10%**	**New value**	**Change**
Population*	175.4	7.37%	Treatment capacity of wwtps	49.3	9.61%
N load per capita	171.5	4.97%	N load per capita	47.4	5.38%
Utilisation degree	170.5	4.40%	N concentration at NI discharges	46.1	2.62%
Rain (not sure to use it)	166.9	2.20%	NI_Wa	45.4	0.91%
Total Infiltration	166.9	2.19%	N concentration at GW+AWI	45.3	0.70%
NI_Wa	166.7	2.07%	N concentration at Ind discharges	45.2	0.62%
N concentration at NI discharges	166.7	2.02%	N concentration at Sealed Areas	45.2	0.43%
N concentration at Sealed Areas	166.2	1.77%	Ind_wa	44.9	-0.22%
N concentration at GW+AWI	164.2	0.54%	Population*	44.6	-0.79%
Ind_wa	164.2	0.50%	Water losses	44.5	-1.06%
N concentration at Ind discharges	164.1	0.46%	Rain (not sure to use it)	44.5	-1.13%
Water losses	163.3	-0.02%	Utilisation degree	43.2	-3.92%
Treatment capacity of wwtps	159.0	-2.65%	Total Infiltration	42.7	-4.95%

*same results as a 10% increase in per capita consumption.

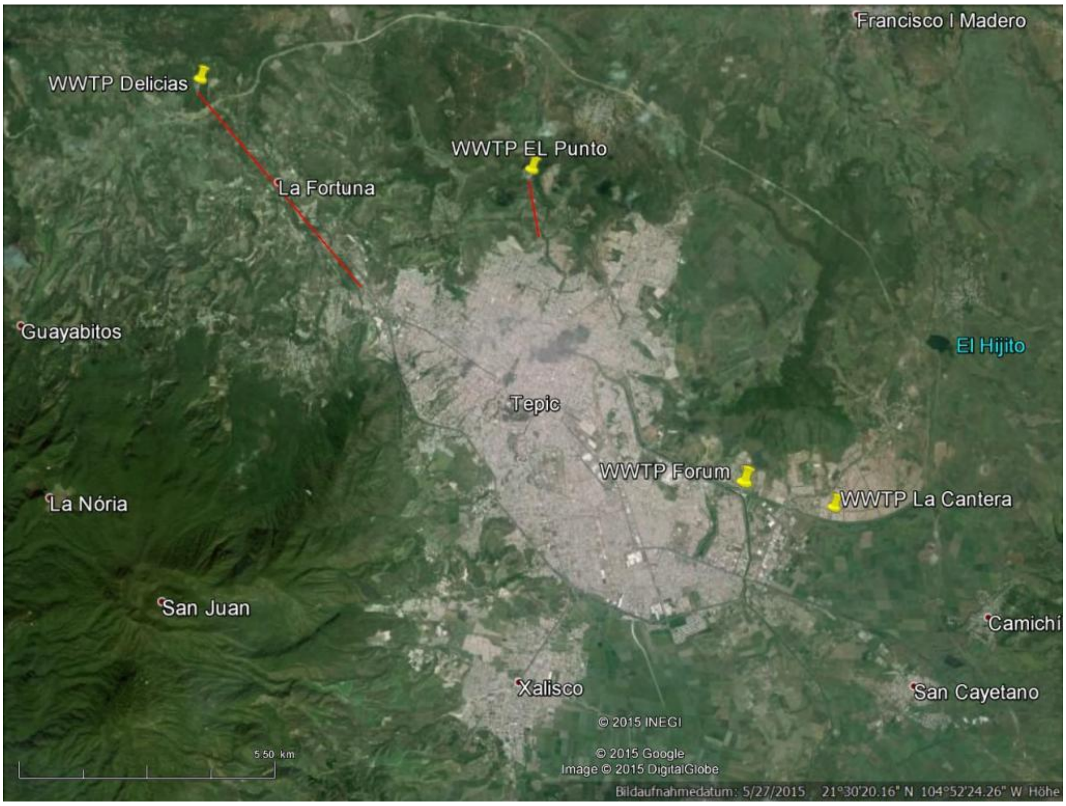
DRY SEASON

UNTREATED N			TREATED N		
Original value	**99.3**		**Original value**	**75.5**	
Parameter changed in +10%	**New value**	**Change**	**Parameter changed in +10%**	**New value**	**Change**
Population*	111.1	11.83%	Treatment capacity of wwtps	79.3	9.35%
Utilisation degree	107.8	8.49%	N load per capita	76.8	5.96%
N load per capita	105.6	6.26%	N concentration at NI discharges	74.5	2.73%
NI_Wa	102.8	3.47%	N concentration at Ind discharges	73.0	0.64%
Total Infiltration	102.2	2.88%	NI_Wa	72.8	0.42%
N concentration at NI discharges	101.8	2.51%	N concentration at GW+AWI	72.8	0.38%
Ind_wa	100.3	0.97%	Ind_wa	72.2	–0.39%
N concentration at Ind discharges	99.9	0.57%	Population*	71.9	–0.89%
Water losses	99.8	0.44%	Water losses	71.5	–1.32%
N concentration at GW+AWI	99.7	0.36%	Total Infiltration	70.1	–3.31%
Treatment capacity of wwtps	92.5	–6.83%	Utilisation degree	68.9	–4.93%

*same results as a 10% increase in per capita consumption.

Annex B - Additional photographic information

View of Tepic from the San Juan mountain (south west).



Location of the Wastewater Treatment Plants in Tepic.
Source: adapted from Google Earth

View of the river Mololoa before entering the city of Tepic (natural river status).

View of the river Mololoa going through the city of Tepic (artificial channel).

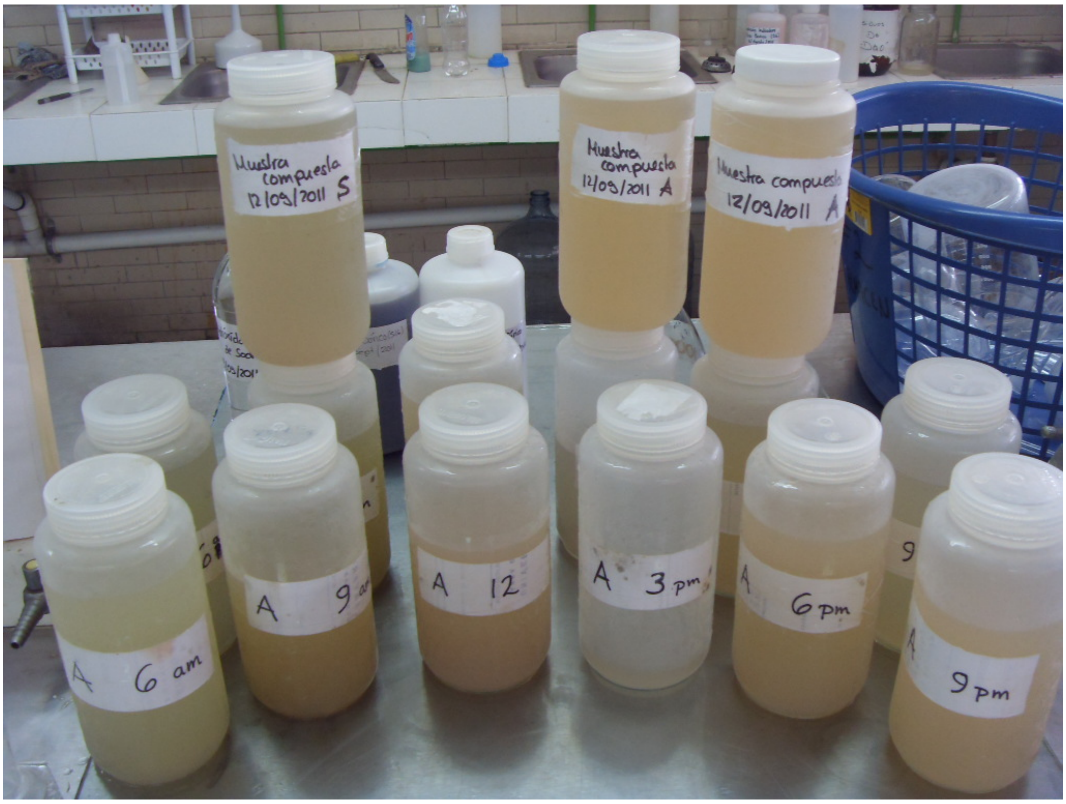
View of one of the tributary channels of the river Mololoa in the city of Tepic (artificial channel).

View of the river Mololoa at the end of its passage through the city of Tepic.

View of the wastewater treatment plant El Punto.

View of the wastewater treatment plant La Cantera.

View of the wastewater treatment plant Delicias.



Collection of samples to prepare a 24 h mixed sample (Evers 2011)

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View of sampling point in neighbourhood *Delicias* (Evers 2011).

View of sampling point in neighbourhood *Los Estadios* (Evers 2011)

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Presentation of results during the 4th IWA Mexico Young Water Professionals Conference in Guanajuato, Mexico

Annex C - Additional investigation tasks in the framework of this thesis

The following is a list of investigation tasks carried out in relations with this research project by bachelor and master students of the Hamburg Technical University under supervision of Gabriela Espinosa and Prof. Ralf Otterpohl. Digital copies of the reports can be requested by email to gabriela.espinosag(at)gmail.com.

D. Rivera (2011). 'Potential to link sustainable urban sanitation with agriculture practice in Tepic Mexico'. Institute of Wastewater Management and Water Protection. Project work. Hamburg University of Technology

M. Suanno (2011). 'Technological innovations suitable for nutrient recovery in Latin America. Modelling of implementation impacts for a case study city'. Master thesis. Hamburg University of Technology, Institute of Wastewater Management and Water Protection in cooperation with the Università degli Studi di Napoli Federico II, Department of Hydraulic, Geotechnical and Environmental Engineering

A. M. Velarde Raudales (2011). 'Application of Suitable Low-Cost Technologies for Wastewater Management in Latin America. Case study: Tepic, Mexico'. Institute of Wastewater Management and Water Protection. Master thesis. Hamburg University of Technology

P. M. Evers (2011). 'Characterization of nitrogen and phosphorous content in domestic wastewater. Case study: Tepic Mexico'. Institute of Wastewater Management and Water Protection. Project work. Hamburg University of Technology

C. Bardou (2012). 'Study on the Potential Groundwater Recharge from Rainwater in the City of Tepic'. Master thesis. Hamburg University of Technology, Institute of Wastewater Management and Water Protection in cooperation with the Institut National des Sciences Appliquées de Toulouse

E. Rámirez Meneses (2013). 'Water in Mexico: current situation and future challenges'. Institute of Wastewater Management and Water Protection. Project Work. Hamburg University of Technology

M. Lafratta (2014). 'Sustainable water management plan of middle-sized cities in Latin America. Case-study of Tepic, Nayarit, Mexico.' Master thesis. Hamburg University of Technology, Institute of Wastewater Management and Water Protection in cooperation with the Università degli Studi di Napoli Federico II, Department of Hydraulic, Geotechnical and Environmental Engineering

Curriculum Vitae

Gabriela Margarita Espinosa Gutiérrez

Personal Information

Date of birth	18.06.1980
Place of birth	Tepic, Mexico
Email	gabriela.espinosag(-a-)gmail.com

Doctoral Studies

Since 11.2010	Ph.D. Studies at the Hamburg University of Technology (TUHH), Institute for Wastewater Management and Water Protection. Doctoral thesis "Material Flow Analysis of the Urban Water System in Tepic Mexico: Integral Evaluation and Improvement Options"

Professional Experience

Since 08.2015	Environmental Fate Modeller. Dr. Knoell Consult GmbH. Mannheim, Germany
08.2009 – 10.2010	Research Associate. Hamburg University of Technology (TUHH), Institute for Wastewater Management and Water Protection. Hamburg, Germany
07.2007 – 07.2009	Environmental Consultant. ERM GmbH. Hamburg, Germany
08.2003 – 05.2004	Environmental Supervisor. CECSA. Santa María del Oro, Mexico

University Studies

10.2004 - 04.2007	Master of Science in Environmental Engineering. Hamburg University of Technology (TUHH). Hamburg, Germany
10.2004 - 04.2007	Master of Business Administration in Technology Management (MBA). Northern Institute of Technology (NIT). Hamburg, Germany
08.1998 – 06.2003	Chemical Engineering (focus on environmental technologies). Universidad Autónoma de Chihuahua. Chihuahua, Mexico

School Education

1995-1998	High school. Centro de Estudios Tecnológicos, Industriales y de Servicios (CETIS) No. 100. Tepic, Mexico
1992-1995	Secondary school. Escuela Secundaria Técnica (ETI) No. 1. Tepic, Mexico
1986-1992	Primary school. Escuela Primaria Gabriel Leyva. Tepic, Mexico