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Assessing material flows in urban systems: an approach to maximize the use of incomplete data sets

G. Espinosa and R. Otterpohl

ABSTRACT

Data scarcity and uncertainty are the main limiting factors for an integral evaluation of the urban water and wastewater management system (WWMS) in developing countries. The present research shows an approach to use incomplete data sets to analyse the flows of water and nitrogen and to make an integral evaluation of the WWMS at a case study city. By means of data validation and model adaptations the use of literature values is kept at the minimum possible and so the current trends for water consumption and pollution in the city are identified. The material flows were calculated as central values with a certain confidence range and met the selected plausibility criteria. Thus, the first essential step needed to identify the challenges and opportunities of future improvement strategies at the WWMS of the city was possible.

Key words | data uncertainty, infiltration, material flow analysis, river pollution, urban water balance

G. Espinosa (corresponding author)
R. Otterpohl
Institute of Wastewater Management and Water Protection.
Hamburg University of Technology, Eissendorfer Str. 42,
21073 Hamburg,
Germany
E-mail: *gabriela.espinosa@tuhh.de*

INTRODUCTION

The knowledge of the material flows in urban cities, i.e. its demands (inputs) and wastes (outputs), is an important aspect in the development of sustainable strategies in terms of resource conservation and environmental protection. This includes the knowledge of the material flows in urban water and wastewater management system (WWMS), which interlinks water consumption and water pollution processes in cities. An integral assessment of the WWMS is essential for the correct planning of any development and improvement measures: a partial assessment could lead to the implementation of measures providing only short-term improvements and to the waste of economic resources. In developing countries, however, the separated assessment of selected processes and water flows of the WWMS is the common practice rather than assessing entire urban water flows in a comprehensive manner. The scarcity and uncertainty of the available data are the main limiting factors for an integral evaluation, together with the lack of communication between the operators of the different infrastructural elements of the WWMS.

The methodology of material flow analysis (MFA) can help to integrate the available information about a system and to calculate its flows under consideration of the data uncertainties (Brunner & Rechberger 2004). The use of MFA and other similar mass balancing approaches for the evaluation of urban WWMS and for the simulation of improvement measures has been investigated in developed countries (Wolf *et al.* 2007; Meinzinger 2010; Kenway *et al.* 2011) as well as in developing countries where the access to data might be difficult (Huang *et al.* 2007; Montangero & Belevi 2008; Martinez *et al.* 2011). MFA has also already been considered as a promising tool for supporting enhanced water policy (Yacob 2008). Nevertheless, large amounts of data for a specific period are required to perform a correct mass balance of the system. When the available data sets are incomplete, literature values can be certainly used to fill in the missing information needs of an MFA. However, the more information about the flows at the specific location is used, the more accurate and realistic the results become and thus an effective support to the WWMS is possible. The available data should be used at a maximum in order to obtain the best possible results.

The objective of the present research was to conceive an approach to handle incomplete data sets about the water flows in a city in order to carry out an MFA of the analyzed system. This paper shows, by means of a case study, how incomplete data sets can be maximized to analyse the flows of water and nitrogen in a city and to perform an integral evaluation of an urban WWMS. The case study location was the city of Tepic in Mexico.

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METHODOLOGY

A model was developed describing simultaneously the water and nitrogen (N) flows at the location following the MFA procedure suggested by Brunner & Rechberger (2004). The simulation of water flows can help to recognize the trends for water use and wastewater management in the city. The N concentration in water and wastewater flows can be used as an indicator of environmental pollution, and thus the simulation of the N flows is useful to recognize pollutant sources and paths in the system.

Figure 1 shows the system setup with the selection of processes and flows for the MFA and it indicates the flows for which no information was available. The system included water input and consumption processes and also the treatment of wastewater at the wastewater treatment plants (WWTPs). The modelling software used for the MFA was STAN© (Inka software). STAN is a freeware especially designed to carry out MFA. The setting up of the MFA models takes place in a graphical manner and it allows concentrating on the system analysis and on the data collection. The calculation algorithm of the program uses mathematical statistical tools such as data reconciliation and error propagation to consider uncertainties in the input data. Details about the software and algorithm can be found in Cencic & Rechberger (2008) and in the official webpage of the software (http:\\www.stan2web.net).

The available information about the water flows in the city of Tepic and their N concentrations dated from years 2003 to 2012 and it was obtained from the registries of the local waterworks operator and from the local authorities as well as from interviews with experts. Tables 1 and 2 show the information available about the city and the type of source from which it was obtained. There was not a complete data set for any of the mentioned years, and the values differed in their sources and reference periods. The degree of reliability (uncertainty) was also variable. For example, some data originated from single measurements and had a high uncertainty while other data originated from continuous measurements and therefore were highly reliable.

To make the most out of the available data and to complete the minimum data requirements for an MFA, several data valuations and model adaptations were carried out progressively and are explained in the next sections.

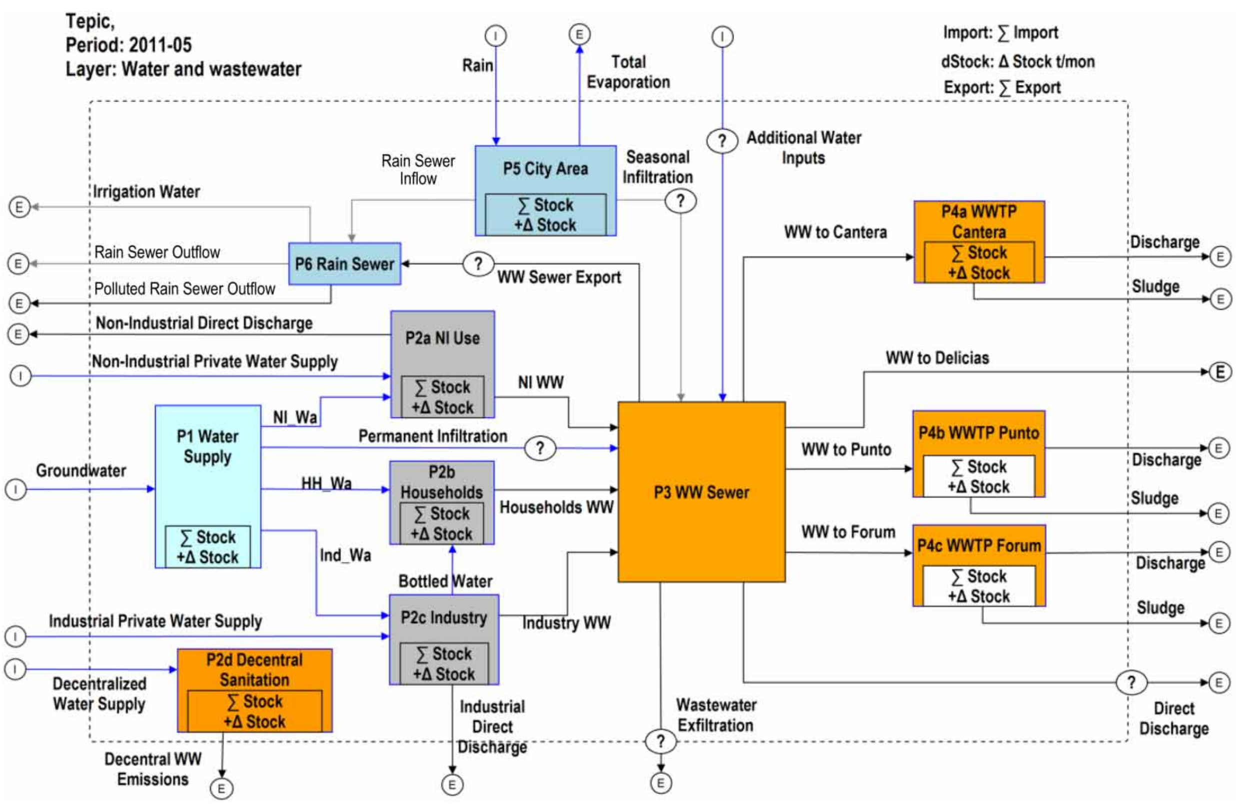

Figure 1 | Model setup for the MFA of year 2011 at the case study city. Abbreviations: E–export, HH–household, I–import, NI–non-industrial, Wa– drinking water, WW–wastewater, WWTP–wastewater treatment plant. A '?' symbol is shown at flows which have not been assessed before at the location.

Table 1 | Categorization of the available data about the case study city (with reference year and source type)

Rain-independent data	Rain-dependent data
Water consumption of all users (2007, 2009, 2012)[a]	Annual and monthly precipitation (2007, 2008, 2009, 2011)[c]
Hydraulic capacity of the WWTPs (2007, 2009, 2011)[a]	**Measured in dry periods**
Direct wastewater discharge from industrial and non-industrial users (2007, 2012)[a]	Nitrogen concentration at the entrance of the WWTPs (2006, 2007, 2008)[a]
N concentration in drinking water (2007, 2010)[a]	Nitrogen concentration at the direct discharge of the sewer (2003, 2008)[a]
Mass transfer coefficients at processes (2007, 2011)[a,b]	**Measured in rainy periods**
Population (2007–2012)[c]	Nitrogen concentration inside the sewer pipelines (2011)[d]
Coverage of the public services for water supply and wastewater disposal (2007, 2011)[a,b]	
City characteristics: size, sealing degree, type of sewer, condition of sewers (2007, 2011)[a,b,c]	

[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 Mexican National System of Statistical and Geographical Information (INEGI).
[d]Information obtained by means of a measurement campaign in cooperation with the local university.

Table 2 | Transfer coefficients

Process	Explanation of transfer coefficient	Source
Materials layer		
Water supply	Water supply delivered to industrial users.	1
	Water supply delivered to non-industrial users.	1
	Water losses.	2
	Ratio of water losses to permanent sewer infiltration.	A
Households and non-industrial users	Water dissipation at households and non-industrial activities due to evaporation, gardening activities, car washing, etc.	L
Sewer	Wastewater exfiltration from sanitary sewer to soil.	3 and L
	Wastewater export from sanitary sewer to rain sewer.	3
City area	Ratio of rain water falling on sealed areas.	3 and L
	Water evaporation from sealed areas.	3
	Rain from sealed areas that runs off to the soil.	3
	Water evaporation from soil.	L
	Rain from sealed areas that goes to the sanitary sewer through house roofs and paved house yards.	3
	Rain from sealed areas that goes to the sanitary sewer through open manholes, damaged slabs, etc.	3
Rain sewer	Total of rain sewer input used as irrigation water for the local agriculture.	3
	Total of rain sewer input flowing directly to the river.	3
WWTPs	Ratio of wastewater input to wastewater discharge at the WWTPs.	L
Nitrogen layer		
WWTPs	Ratio of nitrogen input to wastewater discharge and to sludge.	L
	Denitrification.	

Sources: 1 – calculations in this study derived from the user registry and from the billing information of the local waterworks company, 2 – personal communication with experts from waterworks company, 3 – expert consultation at waterworks company and city council, A – assumption, L – literature.

Data classification and evaluation

The available data were classified in flows or concentrations that could significantly vary according to the precipitation (rain-dependent and rain-independent categories). Secondly, for the rain-dependent data, two subcategories were defined to distinguish data related to the dry or rainy periods. Table 1 presents a summary of the categorization of the available data. In order to maximize the data use while providing an actual view of the status in the city, year 2011 was selected for the simulation.

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 with applicable scale factors (e.g. population growth for the drinking water demand). The uncertainty of the flows was obtained by analysing the probability distribution when possible, by expert consultation and by consulting typical uncertainty ranges from the literature.

Model adaptations

Parallel to the data validation and classification, a series of model adaptations were necessary to compensate for the incompleteness of the data. The use of overall TC at some of the processes allowed for a straightforward calculation of several unmeasured flows in the model and avoided the use complex mass distribution mechanisms. Table 2 shows the TC used in the model according to layer and process and the type of information source for each coefficient.

The available information about the N concentrations in the sewer outflows was not complete for all the flows for any of the seasons. To calculate the concentrations at the remaining unknown flows, a set of equations describing concentration equivalences was used in the model based on the available information. Equations (1) to (3) exemplify these equivalences. See Figure 1 for identification of flows. The use of the equivalence equations underlies the assumption that the dilution patterns remain unchanged in the dry and rainy season

$$C_{\text{Ntot, SewerExport}} = 1 \times C_{\text{Ntot, HouseholdsWW}} \quad (1)$$

$$C_{\text{Ntot, Direct discharge}} = 1 \times C_{\text{Ntot, WWtoPunto}} \quad (2)$$

$$C_{\text{Ntot, Exfiltration}} = 2 \times C_{\text{Ntot, WWtoPunto}} \quad (3)$$

where $C_{i,j}$ is the concentration of element i in flow j.

Additionally, flows with similar characteristics and impacts on the system were aggregated into one flow to reduce the number of unknown variables. For example, all illegal wastewater discharges to the rain sewer and the wastewater flowing from the sanitary sewer to the rain sewer due to wrong connections were aggregated in one single flow named 'WW sewer exports'. It was considered that they all have a short residence time in the sewer, they have eventually the same destination (rain sewer, then the river) and they are expected to have a similar high N concentration (similar to the N concentration in raw domestic wastewater). This flow was then calculated by means of an overall mass transfer coefficient at the process (see Table 2, under 'Sewer' process) and the N concentration of the flow was approximated by using Equation (1).

Likewise, following flows were aggregated in the model as 'direct discharge' flow: all the direct wastewater discharges from the sanitary sewer to the river at different geographic locations (planed or illegal), wastewater being sent without treatment to a nearby agricultural field and the overflow discharge at the main wastewater treatment plant. These are all exports of untreated wastewater towards the river, which have a long residence time in the sewer and therefore they probably have a highly diluted N concentration compared to fresh wastewater. This flow remained firstly as an unknown variable in the model.

Analysis and prioritization of unknown data

After the data valuation and model adaptations, several unknown flows and variables still remained. An analysis and prioritization was made to select which flows could be calculated based on literature sources or expert consultation and which flows should be calculated by the MFA. Priority of calculation by the MFA was given to the 'additional water inputs' and 'direct discharge' flows. These are the largest unknown flows and cannot be obtained from literature sources.

The flows 'seasonal infiltration' and 'permanent infiltration' were modelled based on TC obtained by expert consultation. It was considered that, even when these coefficients might be erroneous or conservatively biased, the calculation of the flow 'additional water inputs' would compensate and the three flows together would provide the total amount of infiltration to the sewer. The calculation of flows 'sewer exfiltration' and 'sewer export' was also based on TC obtained by expert consultation. These coefficients might also be erroneous or conservatively biased. However, the error introduced in the calculations by them was not considered to compromise the veracity of the calculations in a critical manner.

For the N concentrations at the rain-related flows, such as runoff from house roofs and paved surfaces, literature values were used. The total N input to the system from the households was calculated in an iterative manner to obtain the minimum N input necessary to meet the known reference concentrations at the outflows of the sewer. Higher inputs are possible in reality; however, they automatically implicate a higher infiltration to the sewer, and it was decided to work only with the minimum N input and the minimum infiltration.

RESULTS AND DISCUSSION

With the approach used in this study it was possible to assess and balance the water and N flows in the city for year 2011 within an uncertainty range, and it was possible to identify the current trends for water consumption and pollution in the city as well as the current strengths and challenges of the system.

To exemplify the results obtained under this approach, the main findings at the case study location are discussed in this section. The verification of the model was made by means of a plausibility analysis for selected criteria and it is discussed afterwards.

Main findings related to water and nitrogen flows

A total groundwater input to the city of 72.5×10^6 m^3 $year^{-1}$ $\pm$ 16% was calculated, equivalent to 90% of the aquifer's available water (based on availability published by Comisión Nacional del Agua (2009).

The water consumption per capita at households was calculated based on the number of inhabitants and on the information provided by Sistema de Agua Potable y Alcantarillado (public water supply and sewer works company) regarding yearly water abstraction volumes, water losses and service coverage. The calculated domestic consumption per capita was 0.264 m^3 day^{-1}. This is considered as a high consumption, given that 90% of the registered users are categorized as 'low socioeconomic level'. The planning guidelines in Mexico determine an amount of 0.130 m^3 day^{-1} for this socioeconomic level in a city like Tepic with mild warm weather (Comisión Nacional del Agua 2007).

A comparison of the water supply sources and the wastewater disposal paths was made according to user types (Figure 2) based on the MFA results. It was found that the withdrawal of water from public sources and the use of the public sewer as a disposal channel for wastewater were preferred to other supply and disposal forms. Households were identified as the major water consumers in the city as well as the major contributors of wastewater to the public sewer.

The results shown in Figure 2 indicate a wastewater collection rate of 99% of the generated wastewater in the city in the public sewer. Without any additional water inputs, the WWTPs at the city would have the hydraulic capacity to treat 75% $\pm$ 8% of all collected wastewater. However, the wastewater sewer receives additional water inputs in the

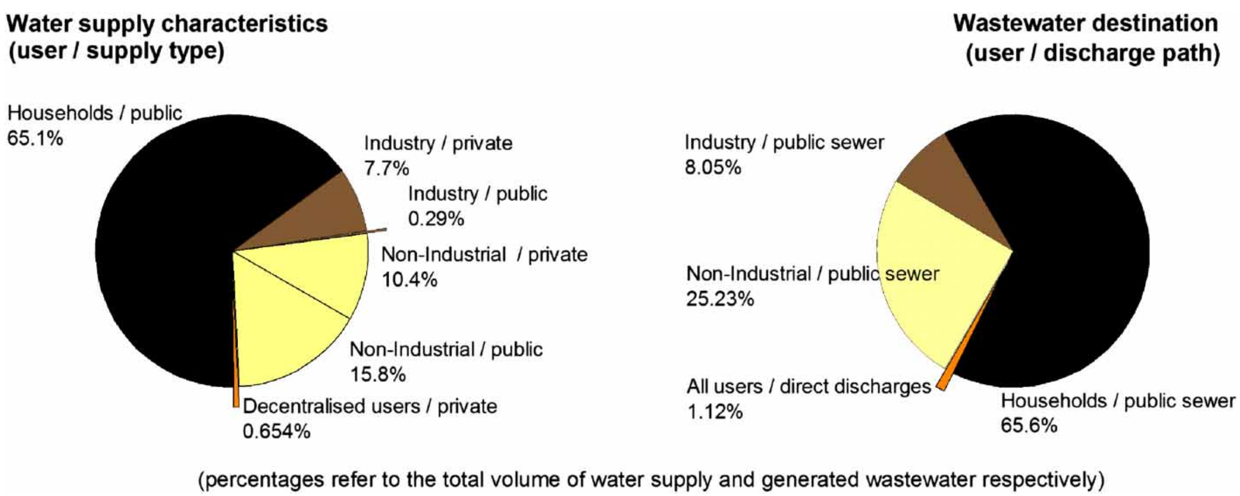

Figure 2 | Characteristics of water supply and wastewater disposal in the city as obtained from the MFA of the water flows in the case study city.

form of infiltrations. The infiltration calculated under this approach is equivalent in the dry season to 63% ± 38% of the wastewater discharges to the sewer. In the rainy season the infiltration was calculated to be, on average, as high as 185% ± 45%. The calculated annual infiltration was 104% ± 40%.

Thus, the model results indicate that due to the high infiltration rate only 46% of the sewer inputs are conducted to a treatment facility in the dry season; the remaining volume (54%) is directly discharged to the river. In the rainy season the percentage drops even more: 26% of the sewer inputs are conducted to a treatment facility and the remaining 74% are discharged to the environment without treatment.

The sewer infiltration increases the volume of untreated wastewater discharge. Due to the effect of dilution, it also simultaneously decreases the amount of N reaching the WWTPs. The infiltration flow itself does not contribute significantly to the N loads in the sewer. Figure 3 presents a summary of the N mass flows in the system at the import and export routes for the dry and rainy seasons and it specifies the contribution of the infiltration to the total N imports. It is observed that households together with non-industrial users provide the system with the largest amounts of N. On the other hand, the N export through untreated flows is the most common export route. The removal of N by denitrification plays only a marginal role in the system.

Plausibility of results

To verify that the model constructed under the approach described in this paper was correct and to validate the results obtained, a plausibility analysis was carried out. Three plausibility criteria were chosen: per capita water consumption at households, per capita N load from households and total infiltration to the sewer. The plausibility of the model was tested by comparing the outcomes of this study against reference values. When the obtained results fell within the limits of the plausibility range of the reference values, then the model was considered as plausible.

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 Mexican Water Commission (CONAGUA Nayarit) in 2007. The consumption calculated in this study lay inside one standard deviation of the average consumption measured in the reference study. Therefore, the results were considered as plausible.

The second plausibility criterion was the N load per capita at households. Reference values were taken from the literature for a Mexican city, for Latin America and for Europe. The calculated minimum N load per capita was inside the limits of the reference values for Mexico and Latin America and was close to the minimum reference value for Europe. The results obtained in this study were thus considered as plausible. The results of the plausibility analysis for the water consumption per capita and the N load per capita from households are shown in Figure 4.

Details about the seasonal variations of sewer infiltration are seldom found in the publicly available information. Literature values for sewer infiltration in Mexico or Latin America were not found. Therefore, a general comparison with the results of a detailed infiltration study in Germany was made: the study showcased by Lucas (2004) concluded with an average yearly sewer

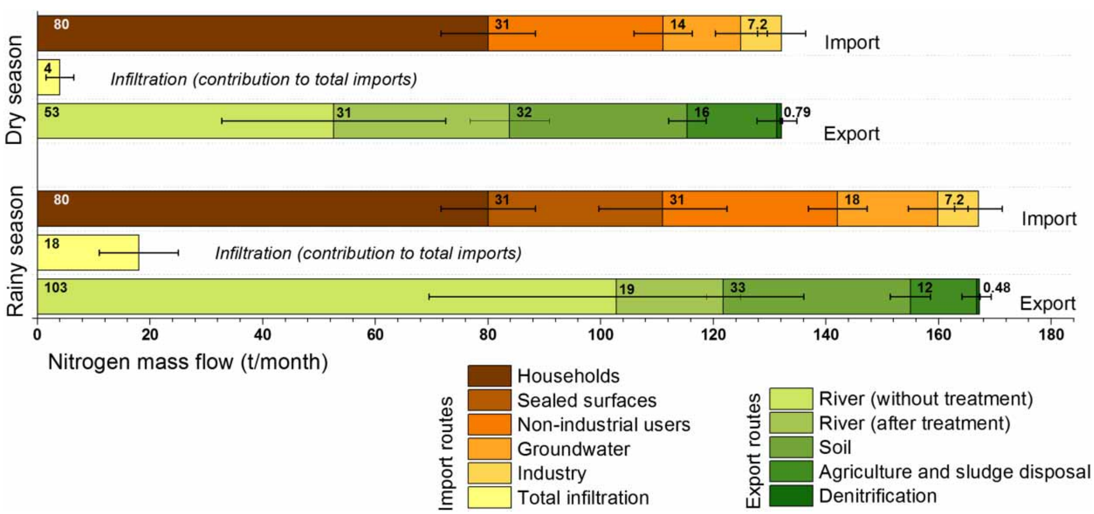

Figure 3 | Import and export routes of nitrogen in the dry and rainy seasons as obtained from the MFA of the nitrogen flows in the case study city.

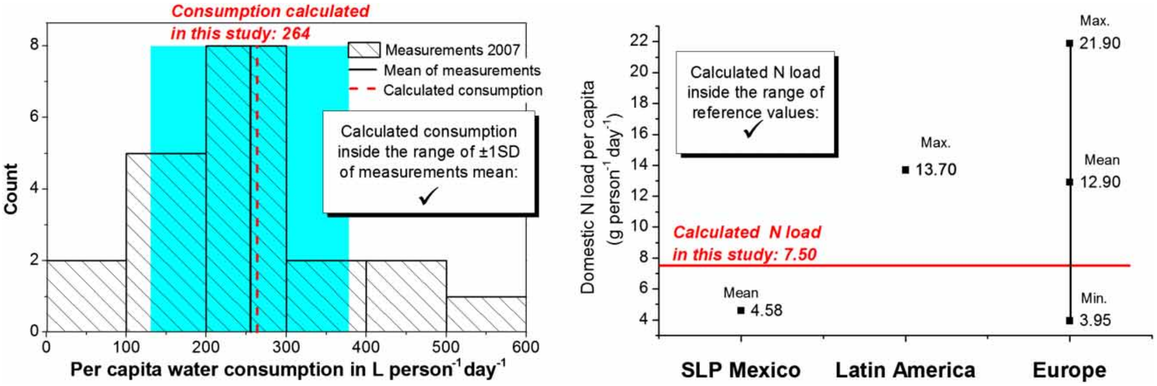

Figure 4 | Results of plausibility criteria for water consumption and nitrogen load at homes. Sources for water consumption – measurement study by a private company on behalf of the Mexican Water Commission (Castillo (2007); unpublished). Sources for N load – San Luis Potosí Mexico: Martinez *et al*. (2011); Latin America: Foster *et al*. (1987) cited by ArandaCirerol *et al*. (2011), p. 496; Europe: Deutsche Vereinigung für Wasserwirtschaft (2008).

infiltration rate of 42% to 70% reported for 1158 WWTPs in Baden-Württemberg. The individual infiltration rates at each WWTP, however, varied from 0% to 500%, most of them being under 250%, and the seasonal variations in one single WWTP could vary from 0% to 600% over the years. Furthermore, Brombach (2002), mentioned in Hennerkes (2006: 25), affirms that the seasonal variations of the infiltration to the sewers could be in a ratio of up to 1:10.

The infiltration calculated for the case study city (60% in the dry season and 185% in the rainy season, seasonal variation ratio 1:3) lay inside the range of the consulted literature values. It also seemed to remain in a relatively low range considering that Germany is a high income country and it is expected that the sewers in Germany present a better general condition than in Mexico due to improved and regular maintenance practices.

SUMMARY AND CONCLUSIONS

The approach taken in this study to maximize the use of incomplete data sets proved to be useful to simulate the flow of water and nitrogen in Tepic despite the limited data availability. The use of literature values was unavoidable; however, by means of data valuations and model adaptations it was kept at the minimum possible. The material flows were calculated as central values with a certain confidence range, and the selected plausibility criteria were met. Thus an approximate, yet reliable, mass balance of the selected substances at the location was made and an integral evaluation of the WWMS at the city was possible for the first time.

After maximizing the use of the available data with the presented approach, it was possible to obtain more information about the water metabolism of the city. For example, the results of the MFA show that the water demand of the city required in 2011 90% of the aquifer's available water. Furthermore, households were found as a major driving force for reducing water consumption and wastewater generation in the city: they present a high per capita water consumption rate of 0.264 m^3 day^{-1} and consume 65% of the total water supply to the city. They are also responsible for 65% of the total generated wastewater.

The existing WWTPs are capable of treating 75% of the generated wastewater (in terms of volume). However, only 46% of the sewer inputs in the dry season and 26% in the rainy season are conveyed to a treatment facility. The exceeding volume is sent to the river without treatment. The infiltration to the sewer is responsible for this, and it was calculated as 60% and 185% for the dry and rainy seasons respectively. Under such conditions of infiltration, the planning of wastewater treatment facilities based only on the volume of wastewater generated by households and non-industrial users, as in conventional approaches, proved to be insufficient to protect the river from direct wastewater discharges. Furthermore, the results of the MFA showed that the majority of the N compounds are released to the environment without treatment: in the dry season only 23% of the total N exports have received a treatment at a WWTP, and in the rainy season only 11%. Nutrient removal from the system is less than 1%.

With a high water consumption and low treatment rate, the city faces important challenges of water availability and river protection currently and in the future.

Maximizing the use of the available data, as carried out in this study, was a first essential step needed for an integral assessment of the water and wastewater management system in the city and it was useful to identify the challenges and opportunities of future improvement strategies.

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