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ABSTRACT

Water is an important resource for all countries and is crucial for their development. It is a fundamental resource: it allows life on our planet, and from an anthropocentric perspective, it is crucial from all our varied biological, cultural and economic processes. The objective of this dissertation is to propose rainwater harvesting (RWH) as a means to achieve sustainable water management in Mexico. Based on a case study in a single neighbourhood of Morelia, Mexico, this dissertation draws a comparison between mains water (baseline) and RWH, with special emphasis on carbon management benefits. The main finding is that by using RWH there is a potential to mitigate 24.7 tCO_2 per year, meaning that these kinds of projects can enter the Clean Development Mechanism scheme to tackle Climate Change. Regarding the economic analysis, a Net Present Value analysis was carried out which showed positive results, demonstrating the economic viability of the project.

Key words: Rainwater harvesting, sustainable water management, carbon management, climate change, economic analysis, Clean Development Mechanism.

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LIST OF ABBREVIATIONS

CC	Climate change
CD	Cointzio Dam
CDM	Clean Development Mechanism
CER	Certified Emission Reduction Credits
CH_4	Methane
CO_2	Carbon Dioxide
CS	Chapultepec Sur
GHG	Greenhouse gases emissions
GW	Greywater
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
KP	Kyoto Protocol
lpcd	litres per capita per day
lps	litres per second
MDG	Millennium Development Goals
MPP	Mintzita Purification Plant
MS	Mintzita Sump
$MtCO_2$	Million tonnes of carbon dioxide
MW	Mintzita Wellspring
N_2O	Nitrous Oxide
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OOAPAS	Organismo Operador de Agua, Potabilización, Alcantarillado y Saneamiento de Morelia
PND	Plan Nacional de Desarrollo
RW	Rainwater
RWH	Rainwater Harvest(ing)
RWHS	Rainwater Harvesting Systems
SWM	Sustainable water management
tCO_2	tonne of carbon dioxide
TT	Tzindurio Tank
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
VBPP	Vista Bella Purification Plant

CHAPTER I: INTRODUCTION

Because of water's natural scarcity, among some other issues, this resource represents a big concern for the future. UNEP (2011) mentions that water demand will rise by 40% by 2030 if water use efficiency is not improved; and UNESCO (2011) recognises water supply as a challenge, especially in cities.

In Mexico the population will increase to 150 million by 2050 and most of this population will be located in areas with low water availability (OECD, 2013). It is therefore due to the upcoming water issues that the country will have to consider sustainable water management (SWM) as a necessary goal; furthermore, it should be considered as a policy priority. Although there are several options to achieve SWM (e.g. desalination, recycling), due to time limitations this study will consider only one alternative, rainwater harvest (RWH). RWH was chosen because this issue has been somehow already addressed and there is an extensive background on the topic. Moreover, the climate conditions in the country are ideal for harvesting water.

This study is divided into four chapters; the first one sets out the objectives of this study, the motivation for making such analysis, a literature review, and the methodology proposed to achieve the study objectives. The second chapter describes the background of the topics related to this study: climate change and rainwater harvesting. Chapter three presents a case study in a portion of Morelia City in Mexico which employs the methodology proposed to find limitations on it. Finally, the study will use real data to develop an economic assessment to show its economic viability should the project is expanded and implemented in other zones. The case study presented is considered of high importance for the results it will give, for they are directly related with the objectives of the study. Finally, chapter four presents the discussion and conclusions for the study presented here. It also includes the limitations found for the methodology and gives some recommendations for further research on the topic.

OBJECTIVES

The objectives of this study are focused on three main aspects: the methodology for comparing RWH against the conventional water supply process, the carbon management analysis for both processes, and finally the economic assessment of the proposed scheme. Regarding the first aspect, the core analysis will be focused on what has been already done about this issue in other countries and in Mexico. The analysis of such studies will allow pinpointing the theoretical framing and the methodology used in those countries, and the possible applications and/or gaps in the methodology used.

The second objective will be the comparison between the water supply process for both options – the conventional and RWH, from the source to the consumption point. The purpose is to make an estimation of carbon emissions in each case and the difference between such estimation will show if there are benefits to using RWH over the conventional system in Mexico.

Finally, once the benefits are exposed it is required to assess the economic viability of the alternative proposed, the third objective of this study. The benefits and economic analysis will be supported by a case study developed in a zone of Morelia city in Mexico. It is intended to demonstrate by using real data the benefits of this particular water supply alternative and to demonstrate its economic viability. This is aimed to be a template of RWH projects that can be promoted and implemented in other parts of the country.

MOTIVATION

According to the most recent Millennium Development Goals Report (UN, 2013) the target of halving the proportion of the population without access to safe drinking water was met in 2010 by increasing access to improved drinking water sources by 89%. Additionally, according to a United Nations report (UNESCO, 2013), water management is somehow related to all the MDGs and it is even considered key to achieve all the proposed targets. Thus, water is again demonstrated to be of great importance now and for years to come.

Despite the increasing efforts to deliver safe, piped water to communities all over the world, the fact is that safe water will not be available to all people in the near future, meaning that a large proportion of the world's population will remain without access to safe sources of water (Meera & Ahammed, 2006). The lack of safe water availability is due to several factors and CC is worsening the problem by changing rainfall patterns, increasing temperature, and putting on more pressure over already water stressed regions (Adler, et al., 2011).

There has been a great investment in Mexico to increase access to drinking water and sanitation, which helped to increase drinking water and sanitation coverage in the order of 92% and 90% respectively in 2011. By doing so, Mexico exceeded the MDGs and it has set even more ambitious objectives for 2015 (OECD, 2013). Notwithstanding, Mexico has a high vulnerability to global warming effects and water management has been declared a policy of national security (Gurría, 2013). Water is still one of the greatest issues that the Mexican government will have to deal with in the years ahead.

Furthermore, there was a full section related to water in one of the lines of action of the National Development Plan 2007-2012 (*Plan Nacional de Desarrollo, PND*) evidencing the importance of water issues. However, rainwater harvest was mentioned just once and it is not clear if it was proposed as an alternative or even as a complementary water source, or just as a means to recharge aquifers. RWH does not have any legal constraints and the only water subsidy is for the agricultural sector, not for domestic, which is the one being analysed in this study. Hence, there is no logical explanation other than the absence of a thorough study for undertaking RWH projects in Mexico.

Despite the importance of water issues addressed in the last governmental period (2007-2012), the PND for the current one (2013-2018) only mentions the importance of having a responsible water management, increasing water supply and sewage, and increasing infrastructure to control flooding. It is not intended to suggest that these issues are not important, but when it comes to the objectives of this particular study, rainwater harvesting is not mentioned explicitly in the whole document.

In Mexico, water availability is deficient and intermittent, meaning that having piped water within the household does not guaranty a sufficient supply due to the *tandeo* scheme present in many cities.[1] Additionally, this kind of non-continuous supply brings some other issues related to water quality decrease and network contamination (Fondo para la Comunicación y la Educación Ambiental, A.C., 2013).

It is important to pay attention to the challenges that water management in Mexico will have to face in the coming years for they can offset the goals already achieved. According to (UN-WATER, 2013) these challenges are the overexploitation of renewable groundwater, water quality improvement, additional investment requirements, CC adaptation, among others. There is another factor that will affect water availability in Mexico: population growth (INEGI, 2013), which will have a direct influence in the water available for the population. Water availability have been significantly decreasing over time going from 31 m^3 pc/yr in 1910 to 4,200 m^3 pc/yr by 2010 (Ibid.). Albeit the achievements that

[1] *Tandeo* is the scheduled distribution of water. This scheme implies that water is distributed only certain hours per day, certain days per week, or even certain hours per day per week.

Mexico has had regarding to water supply, the country has a high hydric-vulnerability; thus, water availability will be reduced due to population growth and the effects of CC.

The social and economic transformations over the last years have made Mexico a urban country with 78% of its population living in urban areas by 2010, and it is expected this percentage to increase to 83.7% by 2035 (ECLAC, 2010). The population centralization results in a big challenge to provide basic services to the whole urban population, especially because the subsistence of this sector is based in the transportation of services from other regions. The daily resources supply to the cities requires, apart from a high economic investment, a constant flow of energy, with their respective environmental impacts both locally and globally. In Mexico, the share of hydrocarbons accounted for almost 89% in 2011 (Secretaría de Energía, 2011, p. 11); hence, the resources supply to urban areas also represent a significant magnitude of greenhouse gases (GHG) emissions.

There is a close relationship between water and energy: water is used to produce energy and in turn energy is needed for water extraction, purification and pumping. Moreover, both resources are necessary for having a reasonable life quality. Hence, saving water should result in energy savings (Gleick, 1993; Chiu, et al., 2009). However, water and energy saving issues are rarely addressed jointly and within an integral vision during the traditional planning of urban water supply systems (Chiu, et al., 2009). These particular arguments were the ones that gave direction to the current study since the conception of "water should result in energy savings" in turn brings the concept of energy savings resulting in carbon reduction.

LITERATURE REVIEW

RWH AND SUSTAINABLE WATER MANAGEMENT

SWM is a concept that involves water resource management considering intergenerational equity whilst avoiding environmental degradation (Loucks, 2000). According to Torres Bernardino (2011) SWM is the way to solve water issues like water supply, flooding, and sanitation. By harnessing rainwater some of these water issues are addressed and this is why RWH is receiving much more attention and is considered as a water management option by several authors. For instance, Farahbakhsh, et al. (2009) evaluated the impact of RWH on stormwater management and water conservation, and identified barriers to RWH in Canada. Firstly they estimated how much rainwater (RW) could be harvested using a 60-year rainfall historical record, and assuming a 160 m^2 catchment surface and a water tank capacity of 6.500 L (in a three-person household). This estimation was used to model three end-use scenarios (outdoor and toilet; outdoor, toilet, and laundry; and the maximum, all uses except kitchen use) and from that the impact of RWH was made. Another calculation was made using a real case scenario with actual use conditions for a one-year period (October 2006 - October 2007), such conditions were a catchment surface of 100 m^2 and an 8,000 L water tank (in a five-person household). The purpose of this real case scenario was to compare its results to the projections to demonstrate the potential of RWHS.

Regarding the stormwater management, the estimations were based on how much water is harvested and how much is sent to the sewer due to the overflow of the water tank. The idea is that the sum of these values is the amount of water that is considered as the stormwater: comparing them therefore gives an approximation of the ratio that is harvested and overflowed. For instance, if 1,000 L is harvested on the rooftop and 500 L overflow, RWH achieves 50% saving in stormwater use. Evaluating each scenario they found that RWH is most effective when there are more end-uses, this is because a greater demand will allow emptying of the water tank faster, releasing space and allowing the entrance of more RW. For the real case scenario they found that there is a stormwater reduction of 89% due to RWH.

Water conservation in this paper refers to water not used from the mains water; thereby, RWH impact on water conservation is also greater when the number of end-use applications is maximised because water demand is being covered by RW and not by mains water. Moreover, catchment surface is the most important parameter affecting water savings for it defines how much water can be harvested. If the catchment surface is large enough, a greater number of end-use applications can be fed. The real case scenario indicated that RW could offset mains water use by as much as 47% in water-conserving homes (with water demand about 40% of the average) or as low as 13% in non-water-conserving homes.

As regards implementation barriers, the authors based their analysis on another study where a series of stakeholder interviews were carried out to identify key barriers. From 23 barriers, five were identified as the most important ones: cost, liability, limited end-uses, poor differentiation between RW and greywater, and poor awareness and acceptance. However just one will be mentioned for the sake of the argument of the current study: cost. They noted that although cost is perceived as a major barrier, the way it is assessed is not sufficient. Thereby, they make five recommendations to take into account when doing cost-benefit analysis: 1) include avoided costs; 2) analysis conducted from several cost perspectives (private and public); 3) use the same discount rate and time horizon for both compared systems; 4) carry out a sensitivity analysis.

Another interesting study is from Loux, et al. (2012) who evaluated the impact of RW and greywater (GW) systems in California, U.S., finding that these two systems combined have the potential to supply large amounts of the population’s water requirements. Their methodology was based on the projection of scenarios where they compared three housing types with different building scales and densities (a single family home, an apartment cluster, and a mixed use – commercial and housing project). In all cases RW was collected from the rooftops and directed to a water tank. To calculate the harvested water a formula was used including the catchment surface, a runoff coefficient (understood as the catchment system material efficiency factor), and the amount of rainfall in the study zone. Based on their estimations, they found that together RW and GW could reduce more than 25% of water consumption from the conventional water supply.

They also included cost estimations in their methodology, including the major elements of each system (RW and GW) (e.g. price of water tank, pumps, disinfection, pre-treatment, plumbing, and excavation. They found that indeed one of the greatest impediments to the widespread adoption of such systems is the cost, and they analysed this by comparing the total cost of water supplied by the proposed systems to the current one and desalination. Although they recognised that water savings involve energy savings (for water extraction, treatment, and pumping costs are reduced), they did not include these savings in energy costs in their economic analysis. If they would have done so the economic balance might have been more levelled. Furthermore, they also noted that the full cost of externalities were not included, implying that the alternative would have had a better position if externalities were incorporated since “there are virtually no externalities for the [RW-GW] combined system” (Loux, et al., 2012:75).

Similarly, studies developed for Mexico – in particular Mexico City, have made an analysis from different points of views, and also agreed in proposing RWH as a means to achieve a SWM (King, et al., 2011; Oswald Spring, 2011; Torres Bernardino, 2011). The basis of this conception is that RWH has the potential to abate water issues by using the same practice and by addressing different aspects from the same concept. For instance, Torres

Bernardino (2011) evaluated RWH from an administrative point of view finding that although there are several limitations (e.g. three different levels of government are involved in water management, making difficult to reach agreements; the governance periods and administration changes makes difficult to propose long run projects and programmes; the tariff schemes do not reflect the real production cost) it has a great potential to achieve SWM, and has made some policy recommendations for RWH projects including stakeholders' participation; the development of a water culture among the population; and changes in water demand patterns. Her study is different from the available literature found for it is explained from an administrative perspective rather than an academic one. Torres' work is a study that explores RWH differently, it is considered as a link between academia and policy makers, it sets out the RWH potential, explores its limits within the administrative/political view, and proposes and recommends how these limits can be overcome.

It is important to recognise administrative, political, and/or legal constraints for they could be translated into costs, which in turn should be taken into account in the economic assessment. These indirect costs are the so-called transaction costs.[2] In this sense, Torres' work is relevant as it identifies that there are no legal constraints on using RW; moreover, she recognises that this is an issue that goes beyond technical issues; it is rather a political and behavioural issue. Despite this, for the current study these constraints are not taken into account due to time limitations; therefore, in the economic analysis, transactions costs were not present.

It is also recognised that in order to achieve SWM, RWH should be considered just one of the many options available, meaning that RWH alone would not solve all water issues. For instance, from the studies previously analysed the combination of RWH with GW

[2] A transaction cost is the cost of "running the system" and include ex ante and ex post activities, e.g. negotiation and monitoring respectively. Transaction costs may also be understood as *direct* or *opportunity costs* (Rindfleisch & Heide, 1997).

systems is proposed as an alternative water supply (Loux, et al., 2012); and also the combination of RWH with some other technique as a means for stormwater management (Farahbakhsh, et al., 2009). This shows that although RWH has a great potential for addressing water issues, by combining it with some other technique its potential can be exploited (achieving maximum efficiency if context is considered).

Governments all over the world are now elaborating policies that foster the implementation of RWS. For example, in India it is mandatory to incorporate RWHS in new buildings (Meera & Ahammed, 2006); whereas in the Virgin Islands it is compulsory to build RWHS with a catchment area larger than $8m^2$ (Garrido, et al., 2008). Furthermore, some developed countries' governments, such as Germany, Denmark, Australia and New Zealand, are also subsidising these systems in order to promote its use (Meera & Ahammed, 2006). This shows that despite the potential of RWH for achieving a SWM, and the support of governments in other countries, in Mexico little is being done to implement RWH projects. For instance, the main report for water management in Mexico, *Agenda del Agua 2030* (CONAGUA, 2011), vaguely mentions RWH as a means of water supply and fails to provide a tangible proposal for its implementation.

In December of 2012 the agreement, *Pacto por México*, was signed between parties and one of the commitments was to establish a programme to foster RWH infrastructure and storage. To date, such a programme has not been developed and it is not clear the level of commitment from the government towards RWH due to the lack of action, even though there are no legal constraints that prohibit harvesting water: RW is considered as private property when it falls into someone's property (in contrast with some States in the U.S.) (See Torres Bernardino, 2011 for a further analysis on administrative aspects). As already mentioned, legal constraints might imply an extra cost for implementing RWH projects for it involves transaction costs such as permits purchasing, administrative costs, and property modifications; having a direct impact on any economic assessment.

RWH AND CARBON MANAGEMENT

King, et al. (2011) evaluated the connections between energy and water in Mexico, and their findings on RWH for potable uses were that this practice helps achieve policy objectives (water security, energy security, water quality, and carbon management[3]) to secure clean water access in communities. They found that by using RWHS energy consumption for water distribution is avoided, resulting in both energy security and carbon management. This finding goes according to what it is aimed to be proven by the current study; and although their study is rather more theoretical, it sets a framing background that could encourage undertaking RWH projects due to the benefits of achieving different policy objectives.

Apart from the methodology proposed this study aims to demonstrate from a different point of view that indeed RWH has benefits over the conventional water supply scheme and could therefore be considered as a SWM option. In a report made by the Environment Agency (2010) for the UK in which the energy and carbon implications of RWH and greywater were evaluated they considered two types of systems: direct feed,[4] and header tank[5]. In the assessment they also included three components to calculate the carbon footprint: 1)

[3] Definition of the policy objectives: i) Water security relates to consistent and reliable availability of potable freshwater or the services it provides; efforts that increase supply, reduce consumption, or conserve consumption in aggregate enhance water security; ii) Energy security relates to consistent and reliable availability of energy resources or the services they provide; iii) Water quality enhance, relates to effort to reduce human activities' impacts on aquatic systems; iv) Carbon management, efforts to reduce or avoid anthropogenic GHG emissions; v) Renewable energy relates to efforts that generate more energy from renewable sources (not applicable to the current study) (King, et al., 2011, pp. 32-33).

[4] In this system water is supplied to end uses by a demand driven pump. In the UK there is a water supply scheme run by mains water, where water is pumped directly from a reservoir direct to the points of use (e.g. toilets, taps). For example, when a toilet is flushed, the pump registers a pressure drop and will start pumping; hence the pump will run every time there is a water demand (RainWater Harvesting Ltd., 2013).

[5] This type of system uses a water tank located above the points of use, usually on the roof. This way, the rainwater is storage in a cistern, pumped to the header tank, and then water is distributed to end uses by gravity (Environment Agency, 2010).

Embodied carbon, or "cradle to gate" assessment;[6] 2) System operational carbon emissions, which are the emissions associated with electricity use for pumping and treatment;[7] and 3) Mains offset and foul water reduction, which is the water supply and treatment savings, and reduced foul water pumping.[8]

The findings of the Environment Agency were that the RWHS carbon footprint is higher for a direct feed system since the type of tank determines the pumping arrangement needed and in turn the energy consumption for water pumping, therefore the pumping arrangement of the direct feed system requires more energy to function; thus the main factors that determine the operational carbon footprint are the type of tank used and the pumping arrangement. For the current study this is irrelevant for the type of tank used is the head tank, implying that there is a lower footprint for such systems. On the other hand, the embodied carbon footprint[9] is higher for a head tank system, and the main factor that determines this is the water tank size (being directly proportional). However, for the current study it is being assumed that the water tank is already installed in the household, so there is no need to include its construction into the analysis. The overall conclusion of the report is that RWHS (and greywater systems) is more carbon intensive compared to mains water.

As already mentioned, RWHS should consider the local context, and though the findings of the Environment Agency might work for the UK, they can hardly be applied for the Mexican context. This is mainly because in Mexico there is no such mains water system. Mexico predominantly has "head tank systems" since all the households should have a water

[6] They calculated the "cradle to gate" carbon footprint as the sum of material, manufacturing, distribution, components replacement, and delivery to site footprints (Environment Agency, 2010, p. 47).
[7] Operating carbon footprint was calculated as the sum of energy use for (pumping + treatment) multiplied by the electricity emissions factor (Environment Agency, 2010, p. 50).
[8] For this component the carbon benefit of RWH is just the demand reduction for mains water
[9] To understand the concept of "embodied carbon" a comparison with a life cycle assessment (LCA) can be useful. Bearing in mind that an LCA is made from the "cradle to grave", i.e. since the system or process begins till the end of its life period or disposal, the embodied carbon would be only the analysis of the carbon footprint from the beginning of the process till the end-use, not the disposal.

tank to store the water that comes either from the network, from purchase, or from another source (e.g. wells, streams, rivers).

Moreover, the system boundaries are not clear since the report considers a “cradle to gate” assessment only for the RWHS but it doesn’t mention a similar analysis for the mains water system. They should have had considered the mains water plumbing and the source of the water used for supply water from the mains, this pumping also implies an energy consumption and should be computed into the analysis. Furthermore, the energy costs associated with water treatment of water from mains is not considered either. The system boundaries should work the same way for both compared systems; thus, the “cradle to gate” assessment must have been present for both systems.

Additionally, another important point of contrast is the water pumping within the household. In the UK report it is accounted only for the RWHS, not for the mains water. However, for the Mexican context this would be nil since water pumping within the household is always necessary regardless of the water source, at least for this particular case study. This is because if the water comes from the municipality, the water will be stored in the water tank, pumped to the head tank, and then distributed by gravity to the appliances. The same applies for the RWHS: rainwater will be collected and stored in the water tank (storage system), and from there the cycle mentioned before is repeated. Thus, water pumping within the household will be the same for both systems, meaning that the energy consumption will be the same in both cases, hence nil or irrelevant to take into account.

Similarly, a second report carried out by Retamal, et al. (2009) for Australia focused on the households’ water pumping energy consumption (from the cistern to the final use). They also compared two systems: header tanks and trickle top-up systems (similar to the direct feed system from the UK report); and their findings were that the former consumes less energy than the latter (in concordance with the UK report). Although interesting, this finding is irrelevant for the current study, since it does not include the energy consumption for water pumping within the household for what has been already explained above. The energy used in the pumping within the household is again nil for the Mexican context.

Furthermore, in one of the last sections of the Australian report ("Further Investigation Required") the following question is provided: "Are header tanks a viable alternative and how much energy would they save?" (Retamal, et al., 2009, p. 54), and their response is that these kinds of systems are not common in urban/suburban RWHS, and they also question the efficiency of using them in urban systems. Once again, this is an adaptation for a specific context where header tanks are not commonly used and since in the current case study is the other way around (header tanks are assumed to be used in all households) the relevance of the report is limited to the context examined here.

The importance of the three studies mentioned is directly linked to the objectives of this study. The UK and Australian report both conclude that RWH is worse off compared to the conventional water supply system in terms of carbon management, the current study aims to demonstrate otherwise. Moreover, it will demonstrate the importance of taking into account the context, since these reports might hold true for their *own* conditions but would fail to explain others. In this sense, the study from King, et al. (2011) has already contradicted the UK and Australian reports by demonstrating that RWH has indeed an associated carbon management benefit, shedding light on the Mexican context.

Another work worth mentioning comes from a non-profit organization leader in the topic in Mexico, *Isla Urbana*.[10] They have focused on water supply, and just recently they started assessing carbon management. Such estimations are based on the carbon mitigation

[10] *Isla Urbana* has the goal to develop and implement a RWH model that can be adopted on a large scale in Mexico City (Isla Urbana, 2013).

from the purchase of water tank trucks (*pipas*) (Lomnitz, 2012); however, they don´t make direct estimations for the conventional water supply system, showing a gap in the studies that are currently being applied in Mexico, thus the importance of this particular study.

According to the internship report of Austodillo (2012) for *Isla Urbana*, it is intended to install over 1.2 million systems in Mexico City, and though the potential CO_2 mitigation depends on the households' roof size and the purchase *pipas*, it was estimated to abate over 63,000 $MtCO_2$.[11] This is an important starting point and *Isla Urbana* has covered one part of the problem; however more analysis should be made for their analysis is based on households without access to mains water and in need of purchasing *pipas.* This current study attempts to shed light over another perspective currently not covered by *Isla Urbana*, the carbon abatement from households with access to mains water and without need of purchasing *pipas.* Moreover, it will be analysed systems in parallel, the conventional and the alternative rather than just one.

Furthermore, an economic appraisal is missing in their methodology, they know the cost of the RWHS implementation but they are failing to estimate the economic benefits of implementing such systems beyond the users. If they do an economic assessment – or any other kind of appraisal, it could help to encourage these kinds of projects; it will also provide more evidence to encourage government to foster RWH projects, breaking limitations. This current study will provide an economic assessment based on a case study and by this it will attempt to overcome the limitations of *Isla Urbana.*

[11] Million tonnes CO_2

SUMMARY

The practice of harvest rainwater is a very well-studied subject, going from very technical aspects, to its benefits (e.g. on the environment, society) and limitations (e.g. cultural barriers, legal constraints). Despite this, these kinds of technologies are very context-dependent and this is why they need to be reassessed for different local or regional conditions, especially the integral aspects described before for they carry more limitations due to their nature.

The relevant literature found for this study were four reports for three countries (the UK [1], Australia [1], and Mexico [2]), and the work done by a Mexican organisation (*Isla Urbana*). Based on their analysis, results, and methodology, this study will attempt to overcome the limitations found for each study.

Starting with the reports for the UK and Australia, it was explained why the results of negative carbon management reported by RWHS for both reports should not hold true for the Mexican context and should therefore not be applied in Mexico. Hence, the current study not only shows the importance of considering the context, but demonstrates that by doing so the result is positive in this case study.

Regarding the report for Mexico (King, et al., 2011) and the work by *Isla Urbana* it was explained how both approaches have their own limitations as regards to the methodology and the economic assessment respectively, and how this current study attempts to overcome such restrictions by providing a case study and performing an economic analysis for both systems. This does not mean that their work is being undermined. On the contrary, it is important as they have set a standard for the country and their results, along with the results in this current study, support the second report for Mexico (Torres Bernardino, 2011) in which the administration limitations, along with policy recommendations are shown.

METHODOLOGY

It is necessary to analyse systems, the conventional one and RWH, in order to be able to make a comparison between them. The analysis of the conventional process of supplying water will set a baseline that allows contrasting it against RWH, making possible to highlight the benefits of it. The methodology for this therefore is divided in two paths, one for each system. In turn, as there are two other main objectives for this study, the methodology will be disaggregated in two sub-components: carbon management and economic assessment. The methodology proposed for each system hence is described as follows:

i. <u>Conventional water supply</u>

It is required to know the full process of supplying water to population and the requirements of doing so; this is, from water extraction until water is available in the households, including all the stages involved in the process. Bearing in mind the objectives of the study sheds light on the kind of data that is needed. To estimate CO_2 emissions it is required to know the energy consumption for there is a link between energy and emissions. There are estimations in the literature that show such relationship through an emission factor, which is just a conversion factor. Emission factors are different between countries for they are based on how electricity is produced in the country; hence, the one used for this study will be for Mexico.

Water needs to be transported and purified; therefore energy is needed for pumping and operating the purification plants. Since the city water supply is entitled by the city's water operator organism, in this case OOAPAS,[12] all the required data should be obtained directly from them. Once this is established, a methodology for estimating CO_2 can be traced as follows:

1. Identify the source of the water used and the transportation process.

[12] *Organismo Operador de Agua, Potabilización, Alcantarillado y Saneamiento de Morelia.*

2. Identify pumping requirements. If there are different stages during the process is important to know if pumping is required in all of them for gravity may be used in some stages.
3. Obtain the energy consumption for water pumping and purification. Once the transportation process is known and the stages that required pumping are identified, the energy used for pumping should be obtained. On the other hand, water needs to be purified to secure its quality; thus, energy usage for such purposes ought to be accounted for.
4. Once the total energy consumption for water pumping and purification is known, the emission factor is used to estimate CO_2 emissions; thus, setting the baseline.

Regarding the economic analysis it is requisite to know the production cost per litre of water (provided by OOAPAS), and the quantity of water treated. The production cost will show the total cost of water transporting and purifying. Thus, four steps are required:

1. Obtain the production cost for the treated water.
2. Obtain the amount of water treated by the water operational organism (OOAPAS in this case).
3. Obtain the amount of water sent to the study zone.
4. Estimate the cost of water pumping and purifying associated to the water sent to the study zone to set the baseline.

i. Rainwater harvesting

Once the baseline is estimated, the counterpart can be assessed. As regards to CO_2 emissions, for this study RWH is used to collect water in situ, i.e. water is obtained in the same place that it will be used, and need not be sent elsewhere which in turn means no need for pumping. This implies that there are no CO_2 emissions, which when compared to the conventional water supply process the benefits are quite obvious. The procedure by which such a comparison will be made is the following:

1. Identify the average rainfall in the zone.
2. Estimate the water supply. For this it is required to know the households' average catchment surface in the zone in order to calculate the rainwater harvest potential.
3. Estimate the water demand. This is estimated by knowing how much water is required to satisfy water needs of the household members. This includes knowing both daily water requirements per capita (lpcd) and inhabitants in the household.[13]
4. Water supply and demand balance. If the supply is greater than demand (S>D), it means that there is no need of using mains water since the harvested water provides more than is needed. On the other hand, if supply is less than demand (S<D), it means that rainwater is not enough to cover water requirements and consumption from mains water is necessary in order to fulfil water demand. In the latter case it is requisite to estimate the percentage of water demand covered by RWH.
5. CO_2 emissions estimation. In the scenario where S>D, CO_2 emissions that are being reduced are the same value as those emitted by mains water[14]. For the second scenario (S<D), only a proportion of CO_2 emitted by mains water is reduced by RWH[15].

Regarding the <u>economic analysis,</u> the methodology is the following:

1. Identify costs. For this study, the cost refers to the systems installation cost.

[13] For example, if the water demand is 100 L/pc/day and the average inhabitants per household is 4, this results in a water demand of 400 L/day, and around 12,000 L/month

[14] If the conventional process emits 100 tCO_2 for pump and purify the water that sends to the study zone and the RWHS fully covers the water demand of the zone, those 100 tCO_2 are mitigated for there is no need to use water from the mains water

[15] Using the same example as before, if RWH only covers 50% of the demand, it will reduce just half of the emissions, 50 tCO_2 instead of 100 $tC0_2$.

2. Identify benefits. Benefits are divided into two components:

    - Potential income. Carbon can be traded in carbon markets; hence, since there is CO_2 mitigation potential, it can be sold resulting in a potential flow of income.
    - Avoided costs. This point is related to the water supply and demand balance, if O>D the avoided cost is equal to the total cost of producing water; whereas if O<D the avoided costs is a portion of the total cost, i.e. the percentage of water demand covered by RWH. Define and run appraisal method. As already mentioned, a case study will be presented in this study, and an appraisal method selected to economically assess the project: the Net Present Value approach.

CHAPTER II: BACKGROUND

This chapter briefly explains what Climate Change (CC) is, human influence towards CC, and the impacts of CC in our lives. It is important to know that, although CC is a natural phenomenon, our economic activities have an indirect influence over it. This chapter will also explain the mechanism that allows Mexico's participation in contributing to tackle CC: the Clean Development Mechanism (CDM) as laid out in the Kyoto Protocol. This last part is crucial since it sets the context in which the current study could be inserted according to the action options for Mexico.

The last section introduces in brief the practice of harvesting water, its main components, and advantages and disadvantages of using this technology. It also includes a small section to discuss rainwater quality, since it is considered relevant to show that this practice supplies safe water for non-potable uses (e.g. toilet flushing, cleaning purposes, laundry).

CLIMATE CHANGE

Climate on Earth is affected by several factors that operate over long periods of time including natural events (e.g. orbital forces, volcanic activity) (UNEP, 2009). There are numerous gas emissions produced naturally that affect how much solar radiation is held and stored in the atmosphere as heat, and as a result of this, the intricate balance of life is possible on Earth (Valero, 2005; UNEP, 2009). If the composition of the greenhouse gases (GHG) change, this dynamic is affected. The Intergovernmental Panel on Climate Change (IPCC) mentions in its Fourth Assessment Report that human activities result in the emission of four long-lived GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons. CO_2 however is the most important one and together with CH_4 and N_2O, the global atmospheric concentrations of these three GHGs have increased markedly (IPCC, 2007). This report also mentions the possible main sources of each GHG, which are fossil fuels for CO_2, agriculture and fossil fuels for CH_4, and agriculture for N_2O. Hence, human beings play an important role in CC.

According to the Comprehensive Assessment of Water Management in Agriculture (2007), CC will affect all facets of society and the environment, and it will have a very strong effect over water and temperature. The effects of CC are not localised to just one specific outcome but a plethora, not to mention the associations amongst them (e.g. water stress affects ecosystems' dynamic, food production, and health).

CLEAN DEVELOPMENT MECHANISM

The Clean Development Mechanism (CDM) is part of the Kyoto Mechanisms, which in turn are part of the Kyoto Protocol (KP). The KP is an international agreement in which countries agreed to reduce overall emissions by at least 5% below 1990 levels in the commitment period 2008-2012 (UN, 1998). To meet this target countries have two options: do so through national measures, or through market-based mechanism – the Kyoto Mechanisms. There are three mechanisms, however for the purpose of this study, only one will be mentioned, the CDM.

According to the UN website (UNFCCC, 2013), the CDM is the first environmental investment and credit scheme of its kind, it also provides a standardized instrument: certified emission reduction credits (CERs). Moreover, the mechanism fosters sustainable development in less developed countries, whilst transferring knowledge and technology. Any CDM project must reduce emissions levels from baseline or business as usual (BAU) projections. The aim of the CDM is to allow emission-reduction projects in developing countries to earn CERs (each equivalent to one tonne of CO_2 – tCO_2). These CERs can then be traded and sold, and used by industrialized countries to meet their emissions targets. Thus, a new commodity is created and as such, carbon is now tracked and traded like any other commodity. This is known as the "carbon market".

Projects that generate carbon credits can be implemented in a specific technology sector (e.g. renewable energy, energy efficiency, forestry) whether they reduce emissions or sequestrate GHG (Hidalgo, 2009). The main recipient countries for CDM projects are China, India, Brazil, and Mexico (Carbon Market Data Ltd., 2013), and to date Mexico has 311 CDM projects registered, Table 1 shows the number of projects and their status (Carbon Market Data Ltd, N/D); whereas Figure 1 depicts a summary of CDM projects within Mexico (King et al., 2011). The objective of displaying the type of projects that are implemented in Mexico is to show that the only ones relating to water are "waste water" and "new dam" but nothing related to rainwater harvest.

Table 1: Number of CDM projects in Mexico and their status. Source: Elaborated from data from the Carbon Market Data Ltd. (2013)

Status	No. of projects
At validation	27
Register requested	3
Registered	180
Rejected	5
Replaced at validation	14
Replaced validation terminated	2
Request review	1
Validation negative	3
Validation terminated	71
Withdrawn	5
TOTAL	**311**

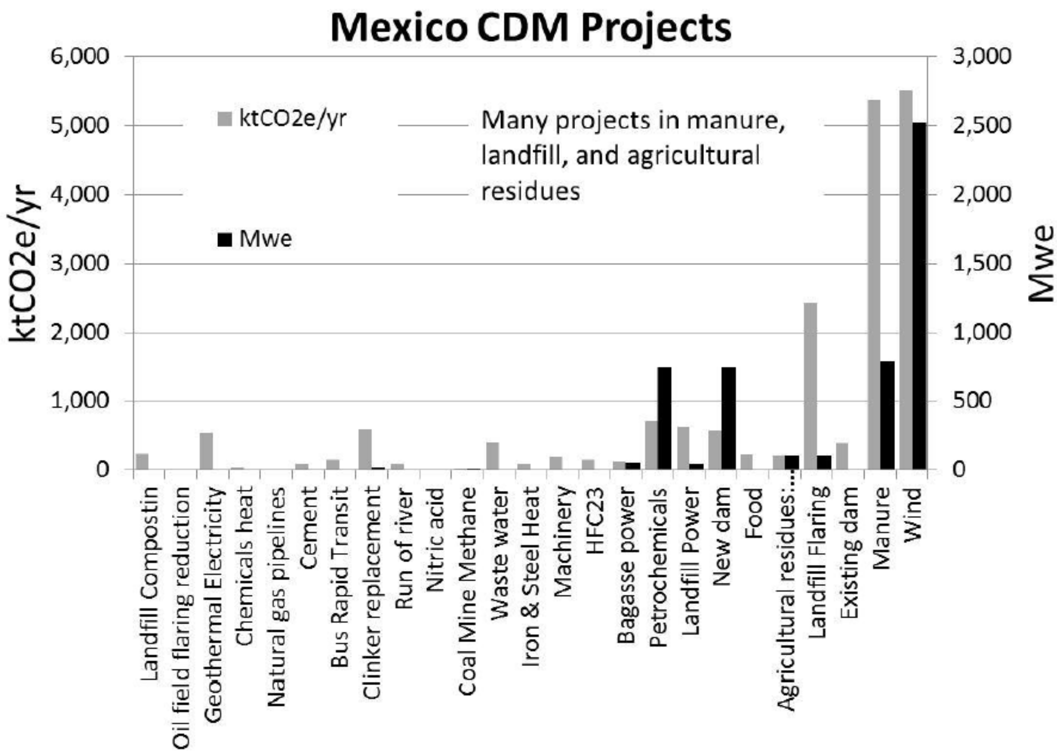


Figure 1: Mexico CDM Projects. Source: King, et al. (2011)

The CDM is an essential part of the theoretical framework of this study since it is the only mechanism that permits developing countries such as Mexico to participate. One of the objectives of the current study is to highlight the carbon management benefits of RWHS projects, and it will also attempt to demonstrate that such projects are an economically viable alternative to sustainable water supply. Since the proposed alternative includes the benefit of mitigated CO_2 due to energy reduction, it has the potential of being considered as a CDM project. Furthermore, as a CDM project, the possibility of generating income would create an economic benefit, which will be considered in the economic analysis.

RAINWATER HARVESTING

Collecting and storing rainwater is a very ancient technique used in many locations all around the world (Dillaha & Zolan, 1985; Sazakli, et al., 2007; Garrido, et al., 2008;

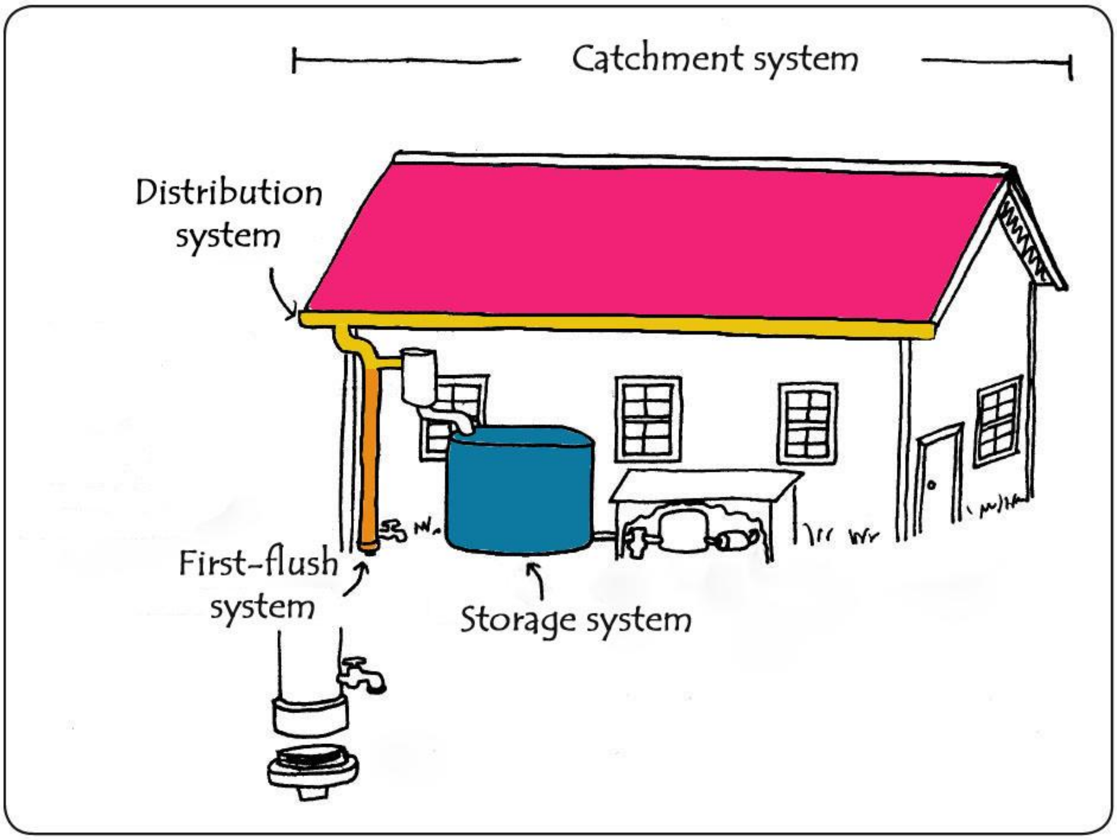
Farahbakhsh, et al., 2009; Gold, et al., 2010); in the case of Mexico the Mayans used the so called *chultún* as artificial water reservoirs (Garrido, et al., 2008). RWH practice has been used in semi-arid areas to alleviate water scarcity (Hatibu, et al., 2006), in arid or remote areas where water supply through water mains is not economically nor technically viable (Sazakli, et al., 2007), and in high or medium rainfall zones as a water supply source (OPS, 2003; OPS, 2004). It is important to recall that the objectives and techniques of RWH are region-specific; hence a technology developed for a particular region should not be used for other regions due to physiographic, environmental, technical, and socio-economic differences (Li, et al., 2004; Jasrotia, et al., 2009).

COMPONENTS

A RWHS essentially consists of intercepting rainwater, gathering it, and storing it for a later use (Farahbakhsh, et al., 2009; Environment Agency, 2010; Loux, et al., 2012). The rainwater is generally collected through the rooftop of the household (interception) (Dillaha & Zolan, 1985; Sehgal, 2008; Abdulla & Al-Shareef, 2009; Kowalsky & Thomason, 2010); the gathering is made through gutters (IDRC, 1990; OPS, 2003; OPS, 2004; Sehgal, 2008; Abdulla & Al-Shareef, 2009); and the storage is in tanks exclusively made for such purpose (e.g. cistern, water tank) (OPS, 2003; Li, et al., 2004; Loux, et al., 2012).

Hence, it can be inferred that a RWHS ought to have three main sub-systems: i) Catchment system, ii) Distribution system, and iii) Storage system (Dillaha & Zolan, 1985; IDRC, 1990; Li, et al., 2004; Zhu, et al., 2004; Meera & Ahammed, 2006; Sazakli, et al., 2007; Chiu, et al., 2009; Abdulla & Al-Shareef, 2009; Song, et al., 2010). However, to increase water quality there should be a fourth sub-system: iv) first flush system (The Lady Bird Johnson Wildflower Center, 2013; Sehgal, 200; Kowalsky & Thomason, 2010; Aftab, et al., 2012), which basically consists of a container where the runoff from the beginning of every rainfall event is retained and diverted. Figure 2 shows all the components of a RWHS.

Figure 2: Main components of a Rainwater Harvesting System. Source: Modified from Hren & Hren (2008)



ADVANTAGES AND DISADVANTAGES

RWH provides a variety of positive impacts and advantages relating to several aspects (e.g. social, economic, environment). Among those advantages reported which are directly related to the argument of this study and support it, the following has to be mentioned:

- Reduces or avoids energy consumption for water pumping (Sehgal, 2008; Gold, et al., 2010; Kowalsky & Thomason, 2010; Carrasco Mantilla, 2011; Loux, et al., 2012).
- Mitigates GHG by reducing energy consumption (Gold, et al., 2010; Kowalsky & Thomason, 2010).

- Reduces the water demand of conventional water sources (e.g. superficial water bodies, aquifers (Sehgal, 2008; Gold, et al., 2010; Loux, et al., 2012).
- Provides additional water supply (Gold, et al., 2010).
- Provides water at the consumption point (or near it) (Sazakli, et al., 2007; Loux, et al., 2012).
- Allows relative independence from conventional water mains (IDRC, 1990; Kowalsky & Thomason, 2010).

The main disadvantage of a RWHS is its cost (IDRC, 1990; Abdulla & Al-Shareef, 2009; Carrasco Mantilla, 2011) as it highly depends on the water tank size and its construction materials, making the storage system the most expensive of all the RWHS' main components (IDRC, 1990; Abdulla & Al-Shareef, 2009). However, one of the main assumptions of this study is that the households already have the storage system by either having a cistern already built or by having any kind of water tank, reducing the cost of implementation.

RAINWATER QUALITY

Rainwater quality is acceptable for non-potable uses (Zhang, et al., 2009) and considered as pollution-free water (The Lady Bird Johnson Wildflower Center, 2013; Meera & Ahammed, 2006; Zhang, et al., 2009). It is recognised that filtration is the only necessary process before storage for non-potable uses (Zhang, et al., 2009), and as already mentioned, by using the first flush system the rainwater quality is significantly increased. Similarly, regular maintenance of the water tanks enhances water quality (Abdulla & Al-Shareef, 2009).

When water precipitates it can absorb pollutants from the air that can acidify it. However, to consider water to be acid it should have a pH of 4 (EPA, 2013),[16] and this is why rainwater is considered to be good quality. In case the water is detected to be more acidic, and due to the rainwater's low dissolved salts and minerals, it is possible to add a minimum quantity of neutralizer chemicals to adjust pH (Sehgal, 2008).[17]

Nonetheless, for potable uses it is highly recommended to use further treatment (Meera & Ahammed, 2006; Sazakli, et al., 2007; Sehgal, 2008; Adler, et al., 2011; Aftab, et al., 2012), including a routine maintenance of the system (Adler, et al., 2011; Aftab, et al., 2012). It is also recommended to add chlorine to the water at least once every rainy season (June-September in Mexico) – preferably after the water tank is full (Abdulla & Al-Shareef, 2009)-, and to clean the catchment surface before the rainy season (Abdulla & Al-Shareef, 2009; Lomnitz, 2012).

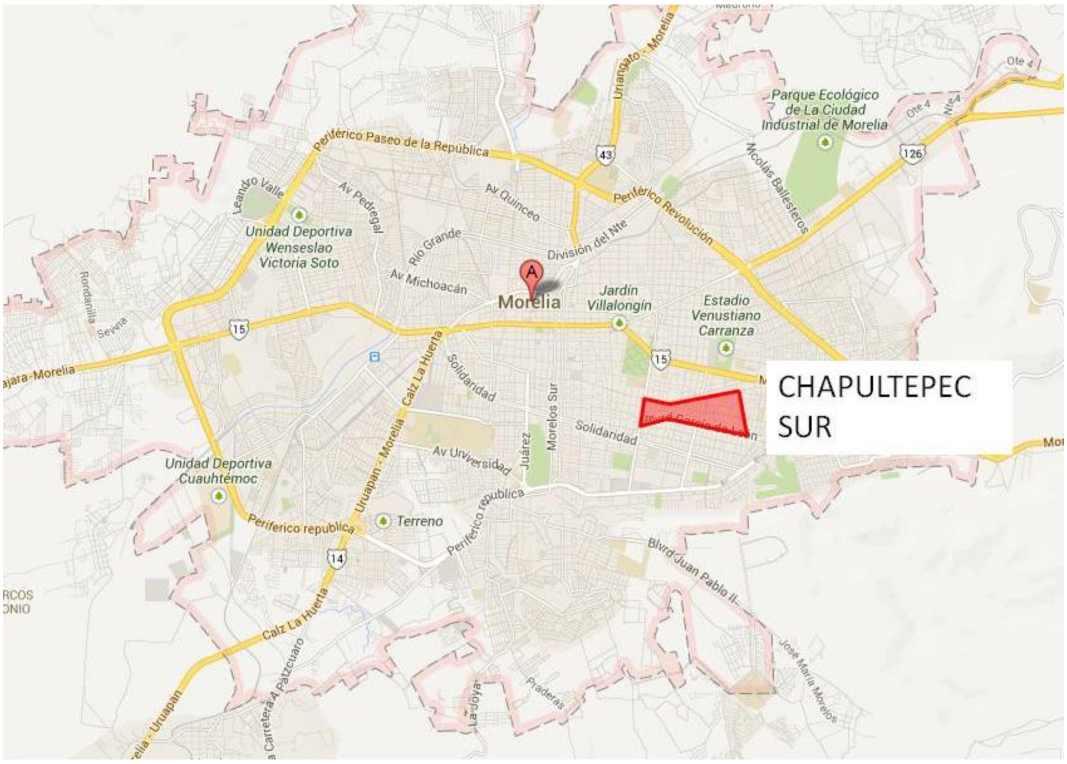
[16] Pure water has a neutral pH of 7, clean water has a pH of 5.6, and acid rain is between the range of 4.2 - 4.4 (EPA, 2013).

[17] Sehgal (2008, p. 7) recommends the use of baking soda since it is widely available and safe for domestic use. The measure he mentions is 1-2 tablespoons per 1,000 litres to neutralize the acidity of the rainwater.

CHAPTER III: CASE STUDY

The case study provided is located in the capitol of Michoacán State at the west of Mexico – Morelia. The study zone was narrowed to a single neighbourhood of the city, Chapultepec Sur (hereafter CS), located at the south-west of the city (see Figure 3). This case study will follow the methodology explained in Chapter I; the required data was obtained directly from the city's water operator, OOAPAS.

Figure 3: Chapultepec Sur neighbourhood in Morelia City, Michoacán. Source: Elaborated from Google Maps



BASELINE: CONVENTIONAL WATER SUPPLY

WATER SOURCE AND TRANSPORTATION PROCESS

The water distributed in the CS neighbourhood comes from two sources: the Mintzita Wellspring (MW) and the Cointzio Dam; and the pumping stages are defined by its origin (OOAPAS, 2012). The water pumping from the MW involves four stages (Ibíd.):

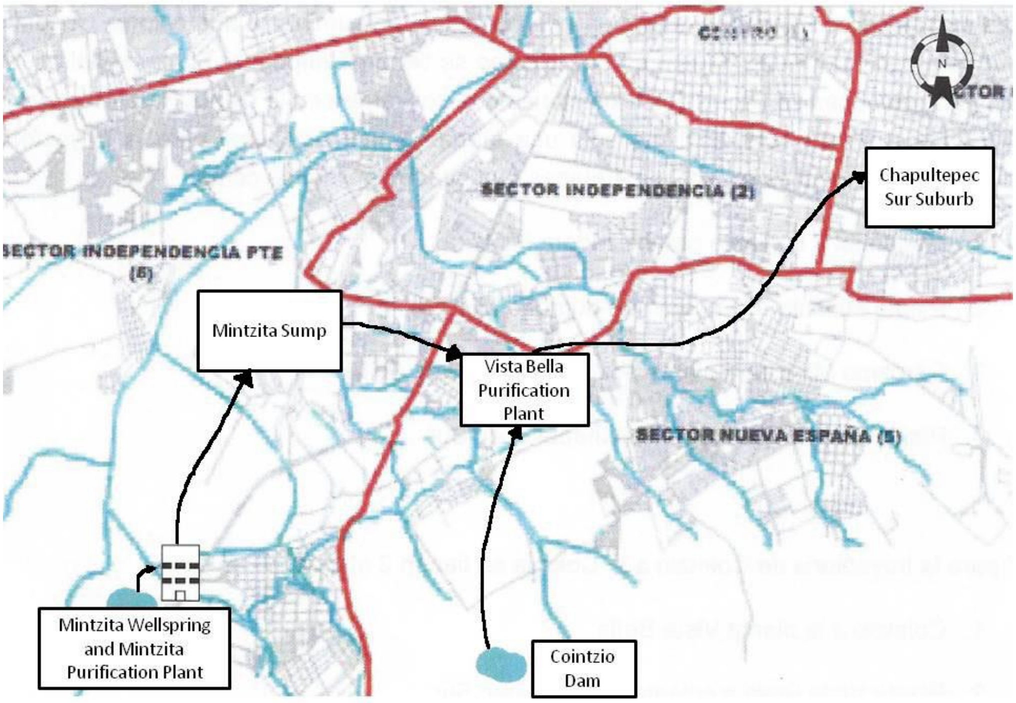
1. Water is extracted and pumped from the Mintzita Wellspring to supply the Mintzita Purification Plant (MPP), where it is purified.
2. Water from the MPP is translated to the Mintzita sump (MS) by gravity.
3. From the sump, water is pumped to the Vista Bella Purification Plant (VBPP) where it is stored.
4. Water is distributed to several neighbourhoods throughout Morelia (among those, the CS) from the VBPP by gravity.

Regarding to the water that comes from the Cointzio Dam (CD), there are only two stages involved (Ibíd.):

1. Water is extracted from the CD and translated to the VBPP by gravity.
2. Water is purified in the VBPP and distributed to several neighbourhoods by gravity.

Figure 4 shows the water transportation process from both origins.

Figure 4: Water transportation process from the Mintzita Wellspring and the Cointzio Dam to the Chapultepec Sur Neighbourhood. Source: Modified from OOAPAS (2012)



ENERGY CONSUMPTION

It was identified that the water that comes from the MW has two stages where pumping is required, and that it is purified in the MPP. Although this water arrives to the VBPP it is not purified again, only stored, for it has already passed through a purification process. Regarding the water from the CD, it does not require pumping and it is purified when it arrives at the VBPP. Moreover, there is another stage where energy is required for pumping. When water arrives to the MS, it is then pumped to the VBPP. Therefore, energy consumption is present in three stages: MPP, MS, and VBPP.

MINTZITA PURIFICATION PLANT

The data provided by OOAPAS for this plant includes the energy consumed for water extraction in the MW (pumping), and global energy consumption for purification that includes complementary services in the MPP (e.g. offices lightening). Table 2 shows the total energy consumption for the period 2009-2013, resulting in an accumulated total of approximately 6,200 MWh, with an annual average of 1,756 MWh.[18]

Table 2: Energy consumption for water purification and pumping in the VBPP

Year	Total energy consumption (kWh)
2009[19]	116,200
2010[20]	1,631,000
2011	1,817,200
2012	1,818,600
2013	851,200
Average (2010-2012)	1,755,600
Accumulated total	**6,234,200**

[18] For the average only years with complete data were used. Since this plant started operations in August of 2009, and the current year has not finished, both years were omitted.
[19] Normal operations started in April
[20] Data available for August-December

VISTA BELLA PURIFICATION PLANT

The energy consumption for purification includes other internal services such as offices, water quality laboratory, and the electro mechanic equipment maintenance area. Table 3 shows the energy consumption for the period 2006-2013, it can be observed that the energy consumption accumulated a total of 1,754 MWh, with an annual average consumption of 234 MWh.

Table 3: Energy consumption for water purification in the VBPP

Year	Total energy consumption (kWh)
2006	260,880
2007	291,040
2008	231,360
2009	228,480
2010	210,000
2011	206,240
2012	216,320
2013	110,160
Average (2006-2012)	234,903
Accumulated total	**1,754,480**

MINTZITA SUMP

Part of the water from the MS is pumped to the VBPP, and the rest is sent to a second location, the Tzindurio Tank (TT). The energy proportion used for both locations is only known in an estimated form and it is established in the order of 80/20, i.e. 80% of the energy consumption is for pumping the water to the VBPP and the remaining 20% is used to send water to the TT. Since for this case study the water sent to the TT is irrelevant it is necessary to calculate the energy consumption associated to the water sent to the VBPP alone (80%). Table 4 shows both the total global energy consumption and the values associated with the water sent to the VBPP. It can be observed that the accumulated total is approximately 80,800 MWh, and the annual energy consumption average is 10,758 MWh.

Table 4: Global energy consumption in the Mitzita Sump, and energy consumption associated to the water sent to the Vista Bella Purification Plant

Year	Global energy consumption (kWh)	Energy consumption associated to the water sent to the VBPP (80%) (kWh)
2006	13,695,139	10,956,111
2007	14,303,071	11,442,457
2008	13,730,229	10,984,183
2009	11,508,185	9,206,548
2010	11,755,579	9,404,463
2011	14,577,979	11,662,383
2012	14,562,345	11,649,876
2013	6,920,298	5,536,238
Average (2006-2012)		10,758,003
Accumulated total		80,842,260

CO_2 EMISSIONS ESTIMATION

In this section the CO_2 emissions for water pumping will be estimated and by this a baseline will be set in order to compare it to the potential CO_2 mitigation of RWH. To estimate CO_2 emissions it is required to know the electricity consumption of the water purification and pumping involved in the process, obtained in previous sections. Once the energy consumption is known, a conversion factor is used to estimate the relation between energy and CO_2 emissions. For Mexico it is estimated that the conversion factor is the following (The Climate Registry, 2012):

$$1MWh = 0.550\ tCO_2$$

Table 5 shows the CO_2 emissions estimation associated with water purification and pumping. Estimations are presented in an annual basis for each stage (MPP, VBPP, and MS); an annual average is presented by using only those years with full available data (2010-2012). Overall it can be inferred that OOAPAS emits **7,080 tCO_2 per year** in average for water pumping and treatment; and during the period 2006-2013 it has emitted around 49,000 tCO_2 in total. These results represent the baseline for this study.

Table 5: CO_2 emissions due to energy consumption during water treatment and transportation

Year	Total energy consumption (kWh)			CO_2 emissions (tCO_2)			
	MPP	VBPP	MS (80%)	MPP	VBPP	MS (80%)	ANNUAL TOTAL
2006	-	260,880	10,956,111	-	143	6,026	6,169
2007	-	291,040	11,442,457	-	160	6,293	6,453
2008	-	231,360	10,984,183	-	127	6,041	6,169
2009	116,200	228,480	9,206,548	64	126	5,064	5,253
2010	1,631,000	210,000	9,404,463	897	116	5,172	6,185
2011	1,817,200	206,240	11,662,383	999	113	6,414	7,527
2012	1,818,600	216,320	11,649,876	1,000	119	6,407	7,527
2013	851,200	110,160	5,536,238	468	61	3,045	3,574
			Average (2010-2012)				**7,080**
			Accumulated total (2006-2013)				**48,857**

COST OF WATER PRODUCTION

Through personal communication with personnel of OOAPAS it was mentioned that the production cost of the treated water is \$16.28 MXN/m^3,[21] i.e. \$0.016 MXN/litre. Since the water sent to the study zone comes from two different sources, it has two different paths. However, there is a point in common where water converges and from that point the next stage is the final destination. This common point is the VBPP and it will be assumed that the water production of the plant already includes the water purified in the MPP, so no further distinctions will need to be made between them.

The annual water production in the VBPP is 19,595,520 m^3 (OOAPAS, 2009) and it is distributed among 20 neighbourhoods, including the CS. Taking into account the production cost provided by OOAPAS, it is estimated that the total cost of water production is \$319,015,066 MXN/year.

According to OOAPAS (2012) the study zone has a 24/7 water supply and an average flow of 17.2 lps; thus, it is estimated that the neighbourhood receives 542,419 m^3/year. It is

[21] Personal communication via e-mail with Engineer Francisco Barboza (2010)

important to note that the amount of water received is not the same amount of water sent by OOAPAS, for there is an estimated loss factor of 40% for Morelia city due to leakage (COEECO, n.d.). Assuming that the leakage is present only from the source until it arrives to the study zone, and there is no further leakage within the neighbourhood, the amount of water that OOAPAS should send to the neighbourhood is **904,032 m^3/year** to assure that 542,419 m^3/year effectively arrives to the neighbourhood. Thus, the actual cost of sending water to the study zone is **$14,717,641 MXN/year**.

WATER SUPPLY ALTERNATIVE: RAINWATER HARVEST

RAINFALL

During the research to get rainfall data for the study zone, it was found that the database from the only reliable source is for the period 1971-2000. Moreover, the National Meteorological Service's website (*Servicio Meteorológico Nacional – SMN*) has two available databases: one from the SMN itself and another one from the Ecology General Direction (*Dirección General de Ecología – DGE*); therefore, the data presented in this section is the average obtained from both sources. Table 6 shows the average monthly rainfall and the total annual for Morelia.

Table 6: Rainfall average in Morelia City for the period 1971 – 2000. Source: elaborated from data from CONAGUA (2013)

Month	Rainfall Average
January	16
February	5.85
March	8.3
April	10.55
May	40.4
June	142.4
July	175.25
August	165.1
September	131.9
October	52.6
November	10.7
December	4.9
TOTAL ANNUAL	**763.95**

WATER BALANCE

The water balance estimation is based on the water supply from the potential rainwater harvesting, and on the household's water demand. The following sections will show how these values were obtained in relation to Morelia, and the resulting water balance will define the CO_2 emissions estimations. It will allow making a comparison between the baseline (mains water) and the alternative proposed (RWH).

SUPPLY

To estimate how much water can be harvested, it is necessary to know the household's catchment surface, and the average rainfall in the zone. Whereas the latter data was shown in the past section, the former one was obtained from a previous study for the same zone (Arroyo Zambrano, 2010).

The basic calculation to estimate RWH considers that each mm of rainfall collected per m^2 yields 1 litre of water; hence the relation is the following:

$$1\ litre = 1mm \times 1m^2$$

Nonetheless, it is necessary to include an efficiency factor related to the catchment surface material, and to the device itself, which are 75% for concrete roofs[22] and 80% for rainwater harvesting systems (RWHS) (Lomnitz, 2012). Thus, the relation mentioned before is modified into the following:

$$L = mm \times m^2 \times Material\ efficiency \times Device\ efficiency$$

$$L = mm \times m^2 \times 0.75 \times 0.80$$

Table 7 shows the results of the rainwater harvest potential per household considering the average catchment surface (125.33 m^2), average rainfall in the zone, and device and material efficiency. It can be observed that the potential water supply from rainwater harvesting is 57,448 L/year per household.

Table 7: Rainwater harvest potential per household

Monthly average rainfall in Morelia (1976-2010) (mm)		Rainwater harvested (L)
January	16.00	1,203.17
February	5.85	439.91
March	8.30	624.14
April	10.55	793.34
May	40.40	3,038.00
June	142.40	10,708.20
July	175.25	13,178.45
August	165.10	12,415.19
September	131.90	9,918.62
October	52.60	3,955.41
November	10.70	804.62
December	4.90	368.47
TOTAL ANNUAL	**763.95**	**57,447.512**

[22] It was assumed that all roofs in the study zone are made from concrete. The efficiency of concrete roofs is of 70-80%, and for this study the average was used.

DEMAND

To estimate the household's water demand it is required to know the water requirement per capita. Two per capita water consumption values will be used in this study, 130 and 115 lpcd. The former value was stated by the Environment Agency (2010) as a goal for 2013, so it could also be taken as a goal reference for Mexico.[23] The latter value was given by regional experts of the study zone, and it was highlighted that this value should be considered as rational or conscious water consumption (e.g. taking 10-15 minutes showers, recycling the washing machine water).

Given the monthly rainfall and per capita daily water consumption, the only value missing to estimate the household's water demand is the number of inhabitants per household. The city council estimates that there is an average of 3.8 inhabitants per household in Morelia (H. Ayuntamiento de Morelia, 2012); therefore, the water requirement per household can be estimated, Table 8 shows the results of this calculation.

Table 8: Household´s water demand based on different per capita daily water consumption

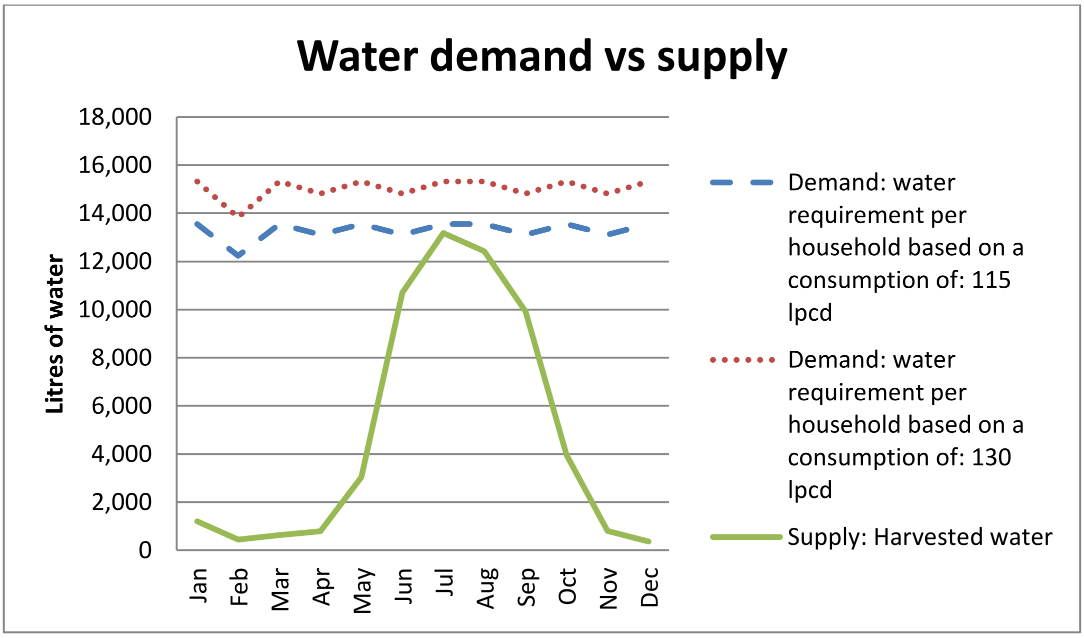
Month	Water demand per household based on different per capita daily water consumption(L)	
	115 lpcd	130 lpcd
January	13,547	15,314
February	12,236	13,832
March	13,547	15,314
April	13,110	14,820
May	13,547	15,314
June	13,110	14,820
July	13,547	15,314
August	13,547	15,314
September	13,110	14,820
October	13,547	15,314
November	13,110	14,820
December	13,547	15,314

[23] In the Environment Agency´s report (2010) they also mentioned that water consumption could possibly be reduced to 120 lpcd depending on new technological development and innovation. Since for this study there is an even lower value proposed (115), a 130 L upper limit was considered appropriated.

BALANCE

Once both the water supply and demand is known, they can be compared to know the balance. Figure 5 shows the balance between water supply and demand, it can be seen that the rainwater harvested is not enough to cover the household's demand (neither 115 nor 130 lpcd). In both scenarios demand is greater than supply (S>D) meaning that it is necessary to consume water from the mains to fulfil the household's water requirements. This is an important point to bear in mind for the following estimations.

Figure 5: Water demand based on different water consumptions and water supplied by RWH



CO_2 EMISSIONS ESTIMATION

Since the water balance describes a greater demand than supply and water from the mains is still required, only a proportion of the CO_2 emitted by the mains water is reduced by the use of RWHS.

Based on previous results the baseline was set and it is known that OOAPAS emits approximately an average of 7,080 tCO_2 per year for sending water to the CS neighbourhood;

and that the accumulated emissions for the period 2006-2013 are almost 49,000 tCO_2. In this section it will be estimated how much could have been mitigated due to the RWHS use for the same period.

As already mentioned, there is a difference between water sent from OOAPAS and water received in the study zone because there is a loss factor. The following analysis is therefore based on the water sent by OOAPAS rather than the water received in the neighbourhood because that is the total water that has been purified and transported; thus the one that accounts for the CO_2 emissions.

By using a RWHS it can only be harvested a percentage of the water sent by OOAPAS, and it is precisely this percentage on which the potential mitigation should be based on, for it shows the emissions that would have been mitigated should RWHS have been implemented. Each household has the potential to harvest almost 57.5 thousand litres, and knowing that in the neighbourhood there are 1,190 households (Arroyo Zambrano, 2010), the potential rainwater harvest in the whole neighbourhood is **68,362 m^3 per year**, representing **7.56%** of the water sent to the neighbourhood.

The average annual CO_2 emission was estimated for the total water produced by the baseline (7,080 tCO_2); however, since only part of the produced water is sent to the study zone (904,032,000 L/year) it is necessary to calculate the emissions associated to this water amount. Thus, the corresponding emissions are 326.62 tCO_2 per year on average. Furthermore, since a RWHS only reduces 7.56% of these emissions the real mitigation for using RWHS in the neighbourhood is in average **24.7 tCO_2 per year**.

Table 9 shows global CO_2 emissions for the total water production (baseline), the emissions associated to the water sent to the neighbourhood, and the potential mitigation due to RWHS use in the neighbourhood. Results are shown on a yearly basis, as an average (years 2010-2012), and as an accumulated total for the period 2006-2013.

Table 9: Baseline CO_2 emissions and potential mitigation due to use of RWH

Year	CO_2 emissions (tCO_2)		
	Baseline	Associated to the water sent to the study zone	Potential mitigation
2006	6,169	284.62	21.52
2007	6,453	297.73	22.51
2008	6,169	284.58	21.52
2009	5,253	242.35	18.33
2010	6,185	285.34	21.58
2011	7,527	347.26	26.26
2012	7,527	347.24	26.26
2013	3,574	164.87	12.47
Average of full years (2010-2012)	7,080	326.62	24.70
TOTAL ACCUMULATED	**48,857**	**2,254.00**	**170.45**

ECONOMIC ANALYSIS

The appraisal method to be used for the economic analysis is the Net Present Value; therefore it is required to know the estimated cashflow of the project, and in turn it is also required to know both the costs and benefits. For this project, costs and benefits were disaggregated in the following:

Costs

The total cost of the project consists in the RWHS implementation in the households, representing the only direct cost. Such investment is a onetime payment and is the only one for the scheme proposed which includes training users to undertake operational and maintenance activities by themselves (the training is included in the installation cost).

Benefits

The potential income of the project refers to CO_2 mitigation for they can be inserted in carbon markets. The rest of the benefits accounts for avoided costs, which are those related to the cost of water pumping and purification to the neighbourhood. Since with a RWHS a percentage of such water is no longer required, a cost of the total process is avoided, thus representing a benefit for this project. Some other benefits exist (e.g. environmental and social); however, because of time constrictions the only ones that will be quantified and mentioned in the current study are those related to the objectives of this study.

COSTS

Households are designed to avoid roof flooding; therefore a roof inclination and drainpipes arrangements are already in place, i.e. catchment and distribution systems are already installed. There are several ways to arrange drainpipes and the most convenient for a RWHS is at the edge of the roof for it only requires sealing them and opening new ones to direct rainwater to the storage system. It was not possible to check the households' roof to know their rainwater drainpipes arrangement for this study; thus, it was assumed that households have the ideal arrangement required for harvesting water.

The RWHS installation cost varies from $6,000 to $8,000 MXN per system (Vargas, 2013)and according to Austodillo (2012) the installation of a RWHS, including labour, materials, and training is approximately $5,000 MXN per system (assuming that the household already has the storage system and pumps). Therefore, another assumption held for this project is that all households have the storage system and pumps arrangement.

Architects from the *Universidad Michoacana de San Nicolás de Hidalgo* in Morelia mentioned that households in the Chapultepec Sur neighbourhood should have a cistern due to water scarcity. Moreover, *Isla Urbana* also mentions that nowadays households should have, if not a cistern, at least some kind of water container due to water scarcity; thus, the assumption of households having the storage system is justified.

Using the average cost of installing RWHS, **$6,333 MXN**, it can be estimated that the total cost of installing RWHS in the whole neighbourhood (1,190 households) would be **$7,536,667 MXN**.

BENEFITS

POTENTIAL INCOME

To estimate the potential income it is necessary to establish a carbon price value, for which a tracking was made during almost three months and an average carbon price of €4.25 was estimated.[24] Additionally, a second carbon price will be used to make a comparison of the effects of carbon market fluctuations: the price is the same used by the IMF in a report for this year, US$25 per tCO_2 (in 2010 dollars) (IMF, 2013). These values represent $72 and $324 MXN respectively.[25]

With the potential CO_2 emissions mitigation already calculated, the potential income can be also estimated. Table 10 shows the results of this calculation for both carbon price values; it shows that if RWHS was installed from 2006, the average annual income could have been approximately $1,800 MXN; whereas for the period 2006-2013 there could have been a total accumulated potential income of around $12,000 MXN, both estimations based

[24] Period from 1 June to 23th August. Data obtained from the European Energy Exchange website (European Energy Exchange, 2013), complemented by data from the Point Carbon newsletters sent by email.
[25] Currency exchange: €1 = $16.80 MXN. Source: (CNN Money, 2013).

on a carbon price of \$72 MXN/tCO_2. The calculation based on a carbon price of \$324 MXN results in a potential annual income of \$8,000 MXN and an accumulated income of approximately \$55,000 MXN.

Table 10 shows the estimations of what *could have happened if RWHS was installed*; however, for the economic analysis that follows, a projection will be made. Thus, the average potential annual income will be used as a basis to calculate the estimated cash flow in next section.

Table 10: Potential income due to CO_2 mitigation

Year	Potential mitigation (tCO_2)	Potential income based on different carbon price values(\$MXN)	
		\$72 MXN/tCO_2	\$324 MXN/tCO_2
2006	21.52	1,560	6,973
2007	22.51	1,632	7,295
2008	21.52	1,560	6,973
2009	18.33	1,329	5,938
2010	21.58	1,564	6,991
2011	26.26	1,904	8,508
2012	26.26	1,903	8,508
2013	12.47	904	4,039
Average of full years (2010-2012)	24.70	1,790	8,002
TOTAL ACCUMULATED	**170.45**	**12,356**	**55,225**

AVOIDED COSTS

OOAPAS spends near \$15M MXN/year in sending water to the study zone, and the associated cost of the water that is obtained by RWH is \$1.1M MXN/year (7.56%). Nonetheless, without the alternative source, in order to assure that the same amount of harvested water arrives in the neighbourhood, OOAPAS should send 40% more due to the loss factor, meaning that it should send 113,937,566 L/year. Hence the avoided cost of the water that is being replaced by the use of RWHS increases from \$1.1M MXN/year to **\$1,854,904 MXN/year**.

APPRAISAL METHOD

Once the costs and benefits of the project have been obtained, the Net Present Value (NPV) can be calculated. The economic analysis for the case study will be a projection, meaning that average values will be used as a base income, assuming also that income is fixed and constant over time. Since two carbon price values were used to calculate the potential income of the project, two different scenarios will be shown; it is important to mention that the only difference between them is the annual income, and the investment remains equal for both scenarios.

EXPECTED CASHFLOW

The project's investment is defined by the RWHS' installation cost. This cost is a onetime investment for there are neither operational costs nor maintenance costs. The installation cost includes training users to teach them how to take care of the devices by themselves. The annual estimated income is the benefits of the project, i.e. avoided costs and potential income due to CO_2 mitigation, and as already explained average values will be used for this prediction. The expected cashflow is shown in Table 11

Table 11: Expected cashflow

Year	Investment	Annual income	
		Scenario 1	Scenario 2
0	-7,536,667		
1		1,856,694	1,862,906
2		1,856,694	1,862,906
3		1,856,694	1,862,906
4		1,856,694	1,862,906
5		1,856,694	1,862,906
6		1,856,694	1,862,906
7		1,856,694	1,862,906
8		1,856,694	1,862,906
9		1,856,694	1,862,906
10		1,856,694	1,862,906

NET PRESENT VALUE

For the NPV assessment it is necessary to define a discount rate and for this study, two discount rates will be compared: 1% and 3%. These values were proposed due to the environmental and social situation we are involved in, and it also represents the importance on intergenerational equity; thus, low discount rates were proposed. This is common practice in environmental analysis of economic phenomena (Perman, et al., 2011, pp. 77-78)

Once the discount rate is set, and considering that the average life of an RWHS is 10 years, the NPV can be estimated. Table 12 shows the resulting NPV for both scenarios using these different discount rates. As it can be seen, the resulting NPV is positive in all cases, demonstrating the economic viability of the project.

Table 12: NPV with different annual incomes and discount rates (1% and 3%)

Year	Investment	Annual income		NPV			
				Discount rate 1%		Discount rate 3%	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
0	-7,536,667			-7,536,667.00	-7,536,667.00	-7,536,667.00	-7,536,667.00
1		1,856,694	1,862,906	1,838,310.91	1,844,461.28	1,802,615.55	1,808,646.50
2		1,856,694	1,862,906	1,820,109.81	1,826,199.29	1,750,112.18	1,755,967.47
3		1,856,694	1,862,906	1,802,088.92	1,808,118.10	1,699,138.04	1,704,822.79
4		1,856,694	1,862,906	1,784,246.45	1,790,215.95	1,649,648.58	1,655,167.76
5		1,856,694	1,862,906	1,766,580.65	1,772,491.04	1,601,600.57	1,606,958.99
6		1,856,694	1,862,906	1,749,089.75	1,754,941.62	1,554,952.01	1,560,154.36
7		1,856,694	1,862,906	1,731,772.03	1,737,565.96	1,509,662.14	1,514,712.97
8		1,856,694	1,862,906	1,714,625.77	1,720,362.34	1,465,691.40	1,470,595.11
9		1,856,694	1,862,906	1,697,649.28	1,703,329.05	1,423,001.36	1,427,762.25
10		1,856,694	1,862,906	1,680,840.87	1,686,464.40	1,381,554.72	1,386,176.94
		NPV		**10,048,647.43**	**10,107,482.01**	**8,301,309.55**	**8,354,298.12**

CHAPTER IV: DISCUSSION AND CONCLUSIONS

Once the comparison between the conventional water supply and RWH have been made the benefits from the latter become clear. Regarding carbon management, to harvest water in the same site (in situ) that will be consumed represents a mitigation of CO_2 because water needs not to be pumped nor purified. Energy consumption results in CO_2 emissions therefore a decrease in energy use means a reduction in CO_2. For the municipality this same reduction in energy consumption means energy cost savings; similarly, a reduction in the amount of water purification chemicals also results in cost savings. The main purpose of RWH is to provide users with water; however, if it is seen as an integral solution it can indirectly address more than one issue, such as CO_2 mitigation.

Although Mexico does not have the obligation of reducing emissions it has undertaken GHG reduction targets to help tackle CC. This shows the importance of pledging mitigation projects, such as RWH. Moreover, these kinds of projects should be implemented on a large scale to have a greater effect and fully harness the benefits, allowing Mexico to meet its goals.

Currently there is an increasing concern over water resources all over the world. Even government reports and development plans for Mexico include chapters regarding water issues, though RW is not yet considered as a possible solution. There is a relatively new scheme to include green technologies in housing named *hipoteca verde* (green mortgages). Nonetheless, RWH is not included in the scheme showing a clear opportunity to explore the topic and propose it as a solution.

The analysis of the baseline did not include emissions due to chemicals used for water purification. Each chemical is associated with an emissions factor that can be accounted for into the emissions estimation, such emissions factors are very specific and data for Mexico was not available. If these factors would have been included into the analysis the benefits of the alternative proposed would have been even greater. Although positive results were obtained in the analysis, it is recommended to include these emissions in further studies.

One more limitation of the analysis is the assumption of everything being constant, this do not hold true because: i) Rainfall patterns will change due to CC (most likely to decrease), having a direct effect over CO_2 mitigation and therefore over the economic benefits; ii) If Mexico still relies on fossil fuel, energy cost is expected to increase, affecting positively the economic analysis; iii) On the contrary, if the Mexican economy enters into a state of decarbonisation, energy cost should decrease, negatively affecting the economic analysis.

If this project is turned into a public policy programme, it is recommended that it is accompanied by awareness programmes seeking to change public behaviour. If consumers don't make a conscious use of the resources (any resource) the solution will become temporal. There is an urgent need to change people's behaviour to assure that resources will be used efficiently and will not be wasted. Therefore, awareness campaigns should be ran in parallel to decrease pressure over resources; this way, programmes can be more effective.

The case study presented in this project is intended to highlight the benefits of using RWHS as a SWM measure, and the results show that there are clear advantages of RWHS over conventional water supply. If we consider that these results are just for a small portion of the city, we can think of the great potential of the project, should it be promoted and implemented in those places where rainwater can be harvested.

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