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Highlights

- Hydrology, Statistics and GIS were regarded in order to develop software with a multidisciplinary approach.
- This informatics tool has an interface through web access but geographically constrained.
- The web application was used for 9 scenarios in urban areas of Mexico.
- Water savings up to 46,500 L were reached in the assessment for average conditions.

Abstract

The current study describes the development of a Decision Support System (DSS) for estimating the optimal tank size of rainwater harvesting systems (RHS). Site-specific conditions are incorporated into the analysis, including those of the local rainfall regime and domestic demand for water, in addition to the desired level of confidence.

The developed DSS is accessible via the interface of a web application, in which the annual efficiency of potential water savings by RHSs is analyzed by a simulation based on historical rainfall data and rainfall distribution.

The developed DSS was applied and validated for nine case studies in the State of Mexico, considering three distinct rainfall regimes and catchments area. According to estimates, an annual potential water savings of up to 46,500 L per household may be achieved under average conditions.

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Keywords

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The developed DSS was applied and validated for nine case studies in the State of Mexico, considering three distinct rainfall regimes and catchments area. According to estimates, an annual potential water savings of up to 46,500 L per household may be achieved under average conditions.

1. Introduction

A rainwater harvesting system (RHS) forms a small-scale unit for saving and storing accumulated rainwater from roofs, gardens, or other impervious surfaces. Saved water may be recycled for non-potable domestic uses (Campisano and Modica, 2014; Mehrabadi et al., 2013). These systems provide an alternative water source and have the added benefit of reducing and retaining water runoff, thereby mitigating the overflow of storm water drainage systems and possibility of flooding (Mehrabadi et al., 2013; Sample and Liu, 2014). However, these systems are infrequently used, in spite of positive findings that have been reported in the scientific literature. According to Imteaz et al. (2011), this may be partially due to the lack of confidence and knowledge from users in regards to the effectiveness of water catchment systems.

The design of a RHS must consider potential interactions stemming from the physical-chemical elements of rainwater, in addition to the catchment infrastructure and means of water transport or storage. Social factors that further influence the use of RHSs may include the domestic demand for water and current availability of water. Economic considerations also include the cost of supplying water, household income, and the concurrent use of other water-saving devices, among other factors (Jorgensen et al., 2009). Furthermore, rainwater has limited uses due to its reduced quality, mainly resulting from atmospheric pollution or sources of contamination present in the catchment area (Silva-Vieira et al., 2013).

In any case, a storage tank is required to regulate the non-uniform distribution of rainfall, both spatially and temporally (Su et al., 2009). During the construction of storage tanks, the availability of space and the cost and placement of materials must be considered. Under this scenario, efficiency analyses of RHSs should be performed in order to reach the minimum necessary tank size.

The variants of a RHS and the likely combinations of its different components has resulted in some of these variables being defined as constants. For example, Mehrabadi et al. (2013) evaluated water accumulation for a range of tank sizes from 1000 to 15,000 L and four different catchment areas, in which demand was considered to be constant. Sample and Liu (2014) performed an optimization of

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RHSs with a tank size ranging from 1 to 80 m^3, as a function of the level of confidence; in this case, both water demand and catchment area were considered as constants. Campisano and Modica (2014) increased the number of possible combinations by using dimensionless ratios to relate the tank size with average rainfall.

Regardless of the method of analysis (optimization or simulation), studies on RHSs have shown that many of the parameters, such as the deficit or potential water savings, tend towards constant values as a function of increasing tank size.

Meanwhile, the present study is performed from a multidisciplinary perspective in order to avoid the assumption of constant values for the variables involved in estimating the tank size of a RHS. To this end, the spatial variation of rainfall was considered. The use of Geographic Information Systems (GIS) facilitates the acquisition, calculation and storage of data which also may be displayed visually as part of a geo-referred system (Eastman, 2012). However, the type of input data and the treatment of the variables, in addition to the output results, are determined by the software requirements engineering, which is oriented towards functionally solving the needs of its users (Insfrán et al., 2002).

The developed Decision Support System (DSS) is capable of estimating the optimum tank size of a RHS under particular conditions by considering the rainfall regime, water demand, and desired level of confidence. The interface is accessible as a web application that analyzes the efficiency by means of a simulation based on historical rainfall data and its spatial distribution. These variables are included in the algorithm of the software in order to facilitate access by a wide range of users from different localities. In this sense, the larger the territory covered by the daily rainfall database is, the more extended the scope of the system is. Nevertheless, in the present study, the tool was specifically applied and validated in the territory of the State of Mexico.

2. Materials and methods

The Decision Support System (DSS) developed in the present study was conceived as one component of an integrative system for the management and implementation of RHSs. The methods for the development of the tool were divided into four stages (Fig. 1) that highlighted the variables necessary for a complete analysis of a generalized RHS.

The first stage involved the conceptual representation of the main elements that compose a RHS. In previous studies (Campisano and Modica, 2014; Imteaz et al., 2016; Karim et al., 2015; Mehrabadi et al., 2013), conceptual models have included depth of rainfall, rainfall savings, transport of saved water to a single storage tank and subsequent water supply, at least for sanitary uses (W.C.). Additional components may be included; for example, Sample and Liu (2014) consider irrigation as one use of recycling saved water, while Li et al. (2010) also implemented processes for the treatment of rainwater and its subsequent use for watering gardens, laundry, or washing cars.

The conceptual model shown in Fig. 2 is the basis of the integrative RHS, and accordingly, of the DSS for the design of tank size. This model integrates the distinct characteristics of a RHS. The number of storage tanks may be increased according to the different water treatments to be implemented and the end uses of recycled water. For example, rainwater from a storage tank with null or minimal treatment may be used for watering gardens. On the other hand, more complex treatments are required for domestic re-use. Water from showers may be considered as an additional source and increase the daily guaranteed volume of water supplied to storage tanks throughout the year.

Another consideration is the difference about type and nature of elements that set up the conceptual model. For example, rainfall and evapotranspiration are natural phenomena that represent independent random variables and that are denoted by real positive values for a daily, monthly, or annual timesteps. Likewise, water demand for domestic uses may be depicted as a positive scalar value or as a constant, while longer timesteps than a subdaily one are considered. Lastly, the variables that describe the characteristics of the infrastructure, for instance the water runoff coefficient, may be represented by fixed scalars.

The scope of this DSS is defined in the second stage of the methods, or in the requirements engineering. This process is part of a larger discipline, in which the needs or restrictions of a system are identified in order to achieve the desired outcome, including the consideration of particular specifications and post-validation (Bourque and Fairley, 2014; Nuseibeh and Easterbrook, 2000; Unterkalmsteiner et al., 2015). In this process, Bagriyanik and Karahoca (2016) have identified two main phases: measurement strategy and mapping phase.

The objective of the first phase is to determine the functional requirements of the user (Bagriyanik and Karahoca, 2016). One priority in developing the first version of a software is to avoid the need for exhaustive input data, or in other words, to allow the software to be executed with minimal information from the end-user side. In this way, the DSS may be handled by a wide variety of users or the entire public. For this reason, the current web application is limited to the basic elements identified in the conceptual model of RHSs. Next versions may contemplate the use of recycled water in irrigation or estimate the tank size of RHSs given two types of water sources (from either alternative: just roof or roof and shower) or water recycling for distinct domestic uses (toward to either: just W.C. or W.C. and washer).

In the second phase of the requirements engineering, classes (or types) of objects and the relationship between them are represented in an interaction diagram (Bagriyanik and Karahoca, 2016). The interaction diagram for the current DSS is shown in Fig. 3 and employs the terminology that is generally used to describe requirement classes in the field of software development (Table 1).

In this interaction diagram, the user generates an event (1) from

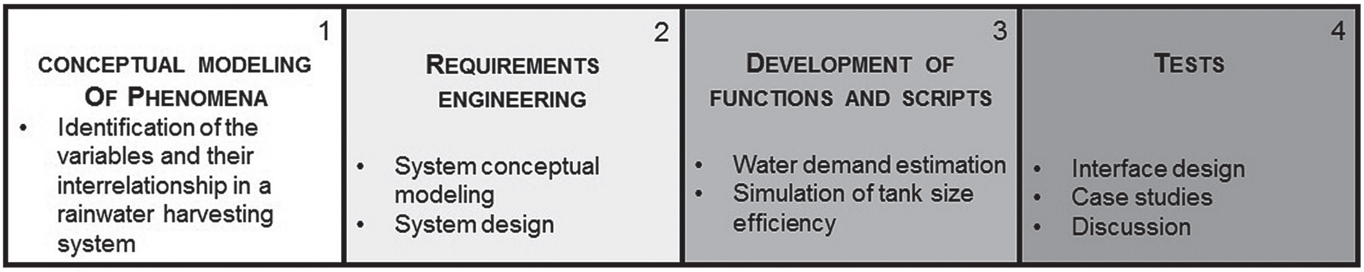


Fig. 1. Development stages of web application to determine optimal storage capacity of rainwater harvesting systems.

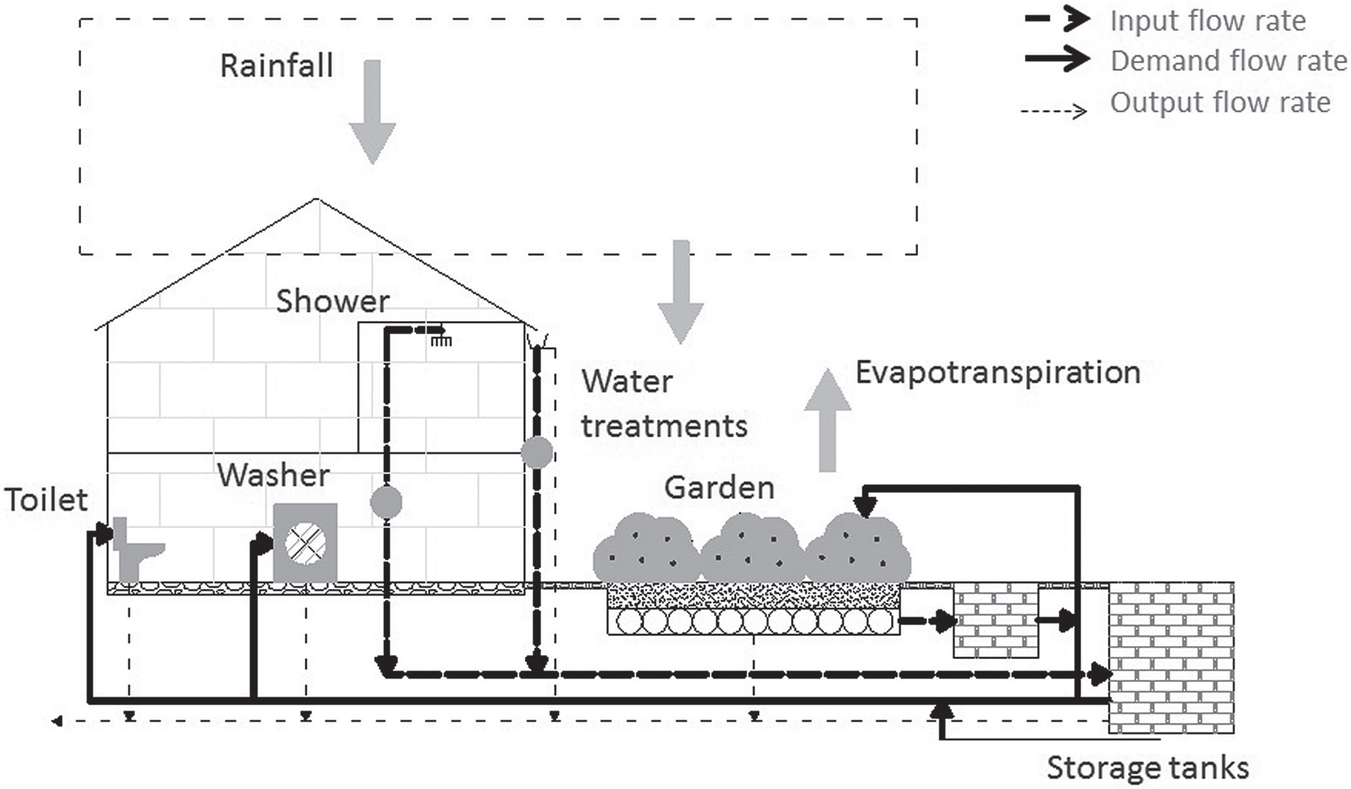


Fig. 2. Conceptual model of a generalized rainwater harvesting system.

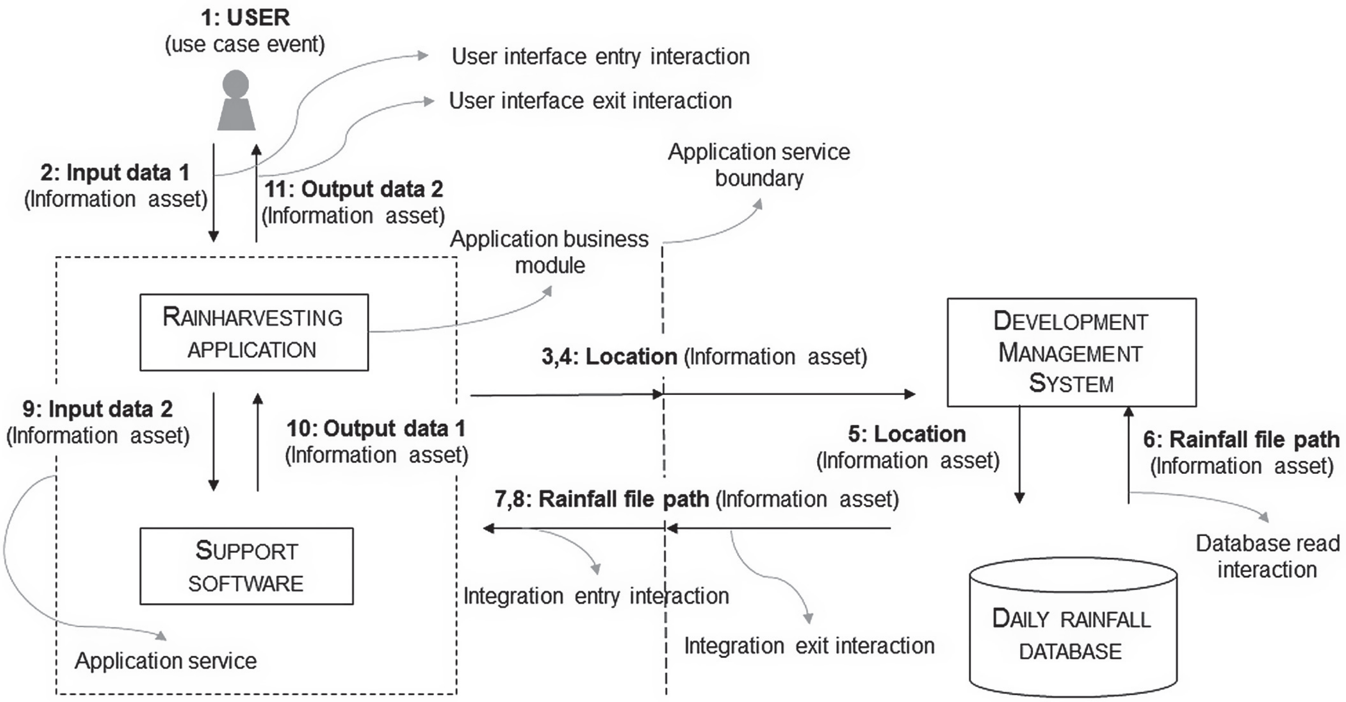


Fig. 3. Interaction diagram of the DSS for estimating tank size in a rainwater harvesting system.

the interface of the web application (end-user side) by providing the lowest possible amount of data (2). It is assumed that users do not know the values for expected rainfall, although they must enter the location of the site where the tank of the RHS will be placed. For this purpose, the software is linked (3,4) to an external system, called Development Management System (SiGeDes- *Sistema Gestor*

Table 1
Requirement classes associated with the rainwater harvesting DSS (from Bagriyanik and Karahoca (2016)).

Requirement class	Description
Use-case	Semi-formal specification of requirements by user submitted to the processes of the Application Interaction Diagram.
Application Interaction Diagram	A type of UML collaboration diagram that depicts use case actors, application services, databases, and interactions between these components; formally specifies the requirements of the use case.
Application Business Module	Software module composed of a user interface that integrates business logic and access to data components.
Application Service	A software application composed of an Application Business Module and an Application Database Module.
Application Service Boundary	A conceptual interface between Application Services or an Application Service and its users.
Use Case Event	Event that initiates use case flow.
Information Asset	Enterprise data model entities exchanged in interactions.
Integration Entry Interaction	Inbound interaction from interfacing Application Services.
Integration Exit Interaction	Outbound interaction to interfacing Application Services.
User Interface Entry Interaction	Inbound interaction from a user of Application Services.
User Interface Exit Interaction	Outbound interaction to a user of Application Services
Database Read Interaction	Interactions of the business module with databases layers for reading Information Assets.

de Desarrollo, in Spanish; Hidalgo et al., 2016), enabling access to databases with site-specific daily rainfall values. After the user provides the geographical location (5), the SiGeDes returns the associated file path and represents it as a daily rainfall vector (6, 7, 8). As long as the file path is known, the application may connect with other software and additional modules (9) in order to perform the necessary calculations for estimating tank size (10). Finally, the output results may be provided in several different formats (table and/or graphs; 11).

In the third stage, the mathematical models for estimating water demand, as well as for analyzing the efficiency of the tank size, were designed regarding an object-oriented programming (OOP). The objective at this stage was to generate reusable blocks of code as part of a structured programming approach in order to increase efficiency in the development of the software (Deitel and Deitel, 2012).

With regards to the size of storage tanks, Campisano and Modica (2014) found differences of up to 17% in the simulated standard deviations of the potential water savings, considering timesteps from 5 min to one day. However, in addition to the difficulty of obtaining subdaily rainfall records, authors as Fewkes and Butler (2000) and Karim et al. (2015) among others have pointed out that modeling with daily inputs provides acceptable results. Therefore, the current study considered available rainfall data and estimated storage efficiency based on a daily mass balance model, as demonstrated in Su et al. (2009).

In daily mass balance, the efficiency of supply Y_j in period j (equation (1)) is represented by a relationship of the accumulated daily deficit Def_i (m^3/day) and the daily demand D_i (m^3/day). The subscript i indicates a daily timestep.

$$Y_j = 1 - \frac{\sum Def_i}{\sum D_i} \tag{1}$$

The daily deficit (equation (2)) is a function of the input water volume q_e (m^3/day), daily demand D (m^3/day), and saved water volume s in the tank (m^3/day). However, according to equation (3), the saved water volume s reaches a maximum value dependent on the tank size S (m^3), and it is unlikely that a typical user would provide the tank size. Indeed, determining the value of the optimized tank size represents one of the main objectives of the Decision Support System (DSS). Under this context, the DSS follows the hypothesis that for greater tank sizes, the estimated annual efficiency of the potential water savings will have lower variation among the rainfall records. In other words, due to the similarities presented by excess volumes (or spills) that overflow tank sizes, results values and their standard deviation will tend towards a constant. In this way, when the system detects values without significant variations in the standard deviation of the simulated annual efficiency, this final value may also be considered to be the maximum tank size.

$$Def_i = \begin{cases} 0 & if\ q_{ei} + s_{i-1} \geq D_i \\ D_i - q_{ei} - s_{i-1} & otherwise \end{cases} \tag{2}$$

$$s_i = \begin{cases} 0 & if \quad q_{ei} + s_{i-1} \leq D_i \\ S & if \quad q_{ei} + s_{i-1} - D_i \geq S \\ q_{ei} + s_{i-1} - D_i & otherwise \end{cases} \tag{3}$$

The daily water volume input and water demand are determined by equations (4) and (5), respectively. In these, r_c (dimensionless) represents a coefficient for estimating runoff losses due to evaporation, d_i and d_c (mm) the depths of daily rainfall and required rainfall to wash the catchment surface area, respectively, A (m^2) the catchment surface area, and n the number of inhabitants; c_t, c_s and c_w (L/hab/day) represent water allocations for domestic uses, in other words for W.C., showers, and washers, respectively. Finally, α_s and α_w are Boolean variables (0/1) to indicate if showers and washers, respectively, are considered in the mathematical model.

$$q_{ei} = \left(\frac{r_c(d_i - d_c)A}{1000}\right) + \left(\frac{\alpha_s c_s n}{1000}\right) \tag{4}$$

$$D_i = \left(\frac{c_t n}{1000}\right) + \left(\frac{\alpha_w c_w n}{1000}\right) \tag{5}$$

In the final stage of the methodology (Fig. 1), the DSS is validated for the study area by means of the web interface. The results of the simulations may be shown graphically for each of the evaluated tank sizes. In addition, for each series of simulated values on the annual efficiency of tank sizes, it is possible to determine the probability of non-exceedance, according to a probability density function, in order to establish conditions for wet, mean and dry years as it could be seen in previous works (Fonseca et al., 2017; Imteaz et al., 2013; Imteaz et al., 2015). Since efficiency values range from 0 to 1, a beta function was selected (equation (6)), in which parameters α and β are given by equations (7) and (8) (Donini et al., 2015); $\bar{y}$ and var(y) are the first moment about the origin (average) and the second central moment in relation with the average (variance) of variable *y*, respectively.

$$P(y) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} y^{\alpha-1}(1-y)^{\beta-1} \tag{6}$$

$$\alpha = \bar{y}\left(\frac{\bar{y}(1-\bar{y})}{var(y)}\right) - 1 \tag{7}$$

$$\beta = \left(\frac{\alpha}{\bar{y}}\right) - \alpha \tag{8}$$

2.1. Study area

The case studies were selected according to the following criteria: availability of data, location of human settlements, and geographical variation in the rainfall regime.

The first version of the web application associated with the DSS developed in this study was limited mostly to the State of Mexico. This region was selected due to the SiGeDes databank (Hidalgo et al., 2016) provides its daily rainfall data, which is made up of 18,250 raster images from 1960 to 2009 (projection UTM: minimum X = 305,590 m, maximum X = 570,096 m; minimum Y = 2,009,623 m, maximum Y = 2,260,954 m). This data was previously generated by Vilchis-Francés et al. (2015) at a pixel resolution of 1700 m, using both linear interpolation in the Idrisi GIS platform (Eastman, 2012) and additional data from conventional climatological stations (CLICOM, 2010).

In Fig. 4, the geographical distribution of the urban settlements as a function of the number of inhabitants may be observed, as well as the rainfall regime in terms of average annual rainfall depth. The State of Mexico has a population of 15,175,862 inhabitants (INEGI, 2016), which the most are distributed in the northeastern portion of the state and to a lesser extent, in the metropolitan area of Toluca.

Although the RHSs in rural areas may improve agricultural productivity (Kumar et al., 2016), they are also a potential alternative for supplying water to urban areas (Karim et al., 2015), which is the focus of this study. Case studies were chosen from each rainfall regime, selecting the urban settlement with the highest number of inhabitants. According to data from INEGI (2016), Ecatepec (1,655,015 inhabitants) has a low average depth of annual rainfall (600–800 mm), while Toluca (489,333 inhabitants) is located into an intermediate level with average rainfall depths of 800–1000 mm. Lastly, Ixtapan de la Sal (17,640 inhabitants) represents the wettest region with an annual rainfall depth of 1000–1200 mm.

The catchment area (roof of building) have a correlation with the socioeconomic level of inhabitants. Therefore, three surface area scenarios were considered based on the information contained in the urban development plans of each locality (H. Ayuntamiento de Ecatepec, 2009; H. Ayuntamiento de Ixtapan de la Sal, 2012; H. Ayuntamiento de Toluca, 2014), as follows: a) 90 m^2 for social interest housing; b) 150 m^2 for average urban houses; c) 200 m^2 for high-end residences. Besides, concrete is the most used building material for all scenarios. In Ixtapan de la Sal and Toluca, the average population density is four inhabitants per household, and for Ecatepec five inhabitants per household.

In relation with water consumption, Umapathi et al. (2013) projected that rainfall contributes nearly 31% of total average demand, which was determined by real time monitoring in Australia.

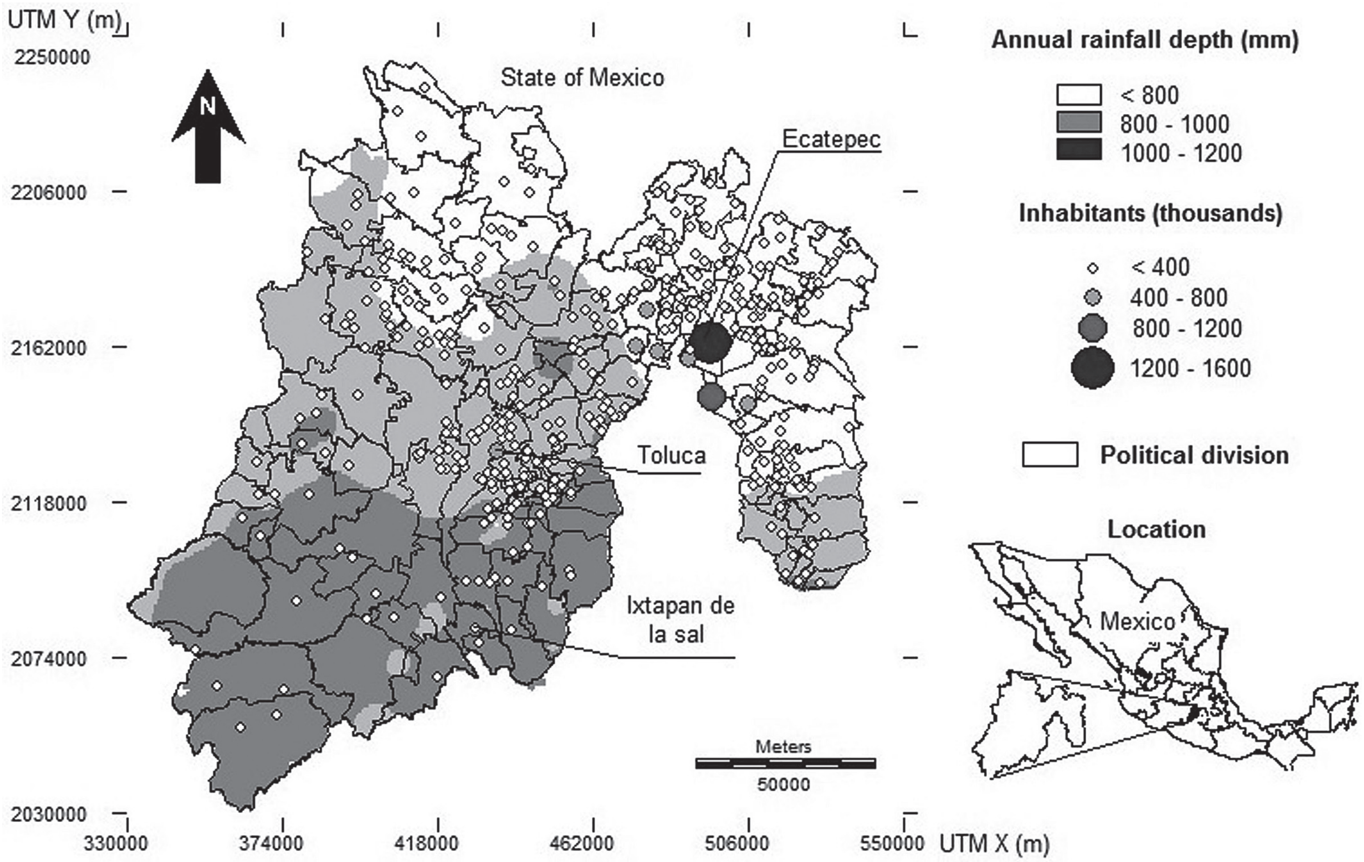


Fig. 4. Location of study cases.

Su et al. (2009) found that 20% of the domestic water demand corresponds to W.C. use (50 L/hab/day), while Sample and Liu (2014) determined a value of 22.7 L/hab/day for the same use. In this study for the State of Mexico, a standard demand of 33 L/hab/day for W.C. was considered, in addition to 82 L/hab/day for showering and 24.6 L/hab/day for washing machines, according to the previous calculations of Maya (2010).

2.2. Development of software

Fig. 5 shows the static structure of the DSS designed in the Node.JS® open-source runtime environment which works on an event-oriented model (Nguyen, 2012). For security reasons and due to online access, the names of some elements were changed. In this structure, it is also possible see external supporting software, which may be seen as: a) imported modules to both the main platform and the interface and; b) executed operations from independent software packages.

The imported modules to the main platform are involved into the element "node_modules," while those via-internet imported to the interface are allocated to the "public" element. This DSS also requires the execution of independent software from Node.JS®: MatLab® (version R2012a) which provides an object-oriented programming, including its own matrix language (Register, 2007) and Python® (version 2.7.8) which allows runtime interactions within a Component Object Model (COM; ActiveState Software Inc., 2016).

The developed modules are located in the "functions" element and are classified according to the platform on which they operate. The files with extension *.js are written in JavaScript, while those with the extensions *.py and *.m are developed for Python and MatLab, respectively. Table 2 describes the modules utilized in the system.

Through the "layer" interface, the "main.js" element processes the user request and provides the results by means of the variables "media" (average daily rainfall), "desv" (standard deviation of average rainfall), "EfanualOut" (matrix of simulated efficiency values for different maximum tank sizes), "SOut" (vector of the values for maximum tank size), and "ProbSeriesOut" (matrix with efficiency values for ranges of non-exceedance probabilities for each value of maximum tank size).

The dynamic relationship among these elements is shown through an Unified Modeling Language (UML) sequence diagram (Fig. 6). A new event from end-user side triggers both data entry (parameters for estimating demand and location provided by the Google Maps API (2015)) to the object main.js and creation of dowithpython.js objects which allow interaction between the modules developed in Python and the M script files to be executed in MatLab. For example, the module EstEf.py do both: a) transfers the file path associated with daily rainfall, as well as the parameters for estimating water demand and; b) executes the functions DemGen, DispGen, and EfAlm.m in MatLab. This latest function (Fig. 7) determines the length of the tank sizes vector. Finally, based on the series of probability values provided by ProbSeries.py to

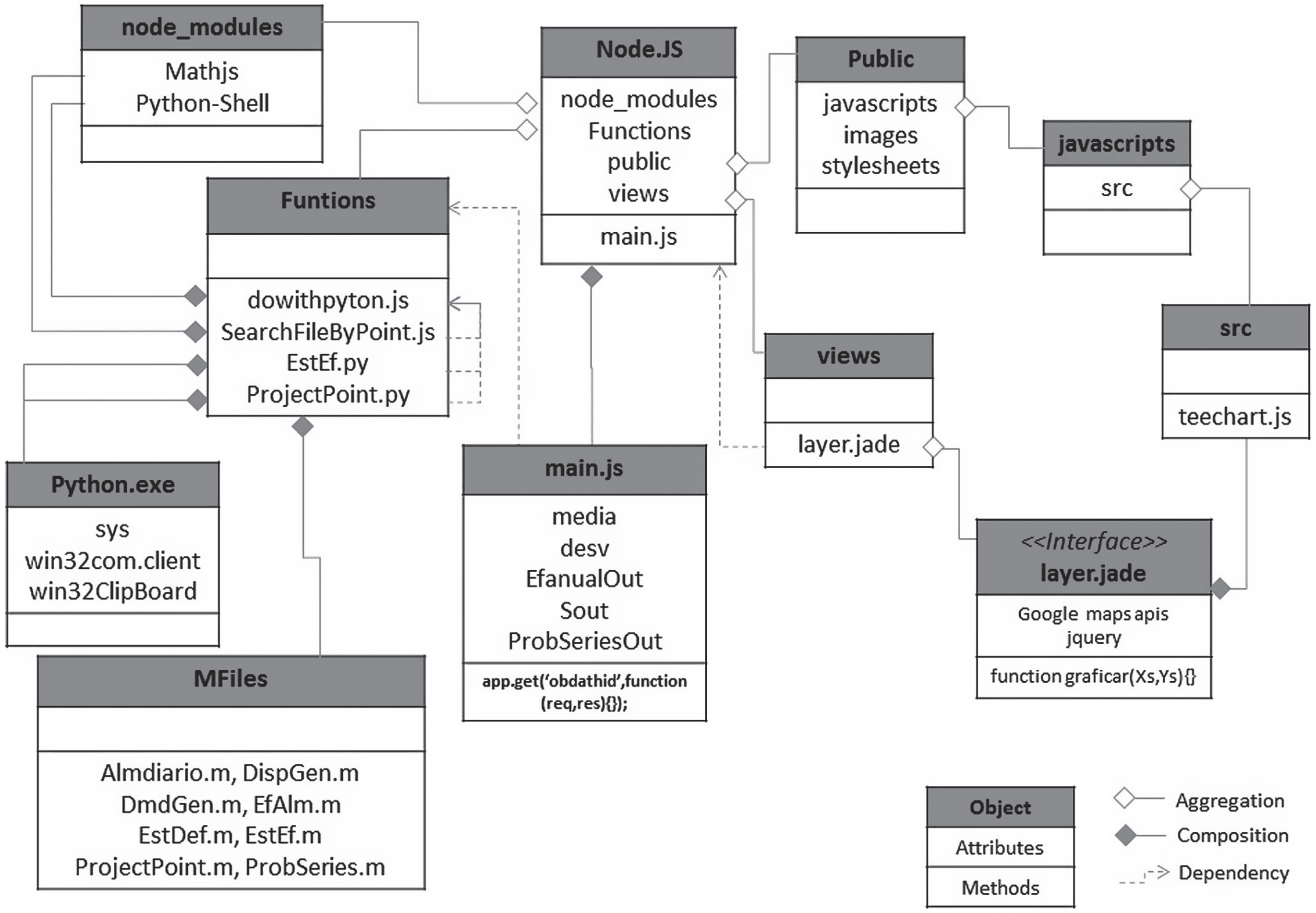


Fig. 5. UML class diagram of the web application.

Table 2
Modules used in the rainwater harvesting DSS.

Name	Language	Description	Source
Mathjs	JavaScript	Extensive math library for JavaScript and Node.js. It features a flexible expression parser and offers an integrated solution to work with numbers, big numbers, complex numbers, units, and matrices.	de Jong (2016)
Python-Shell	JavaScript	A simple way to run Python scripts from Node.js with basic but efficient inter-process communication and better error handling.	Mercier (2014)
dowithpyton	JavaScript	Provides input arguments to be used by a Python script through Python-Shell. Required results are filtered from the script's raw outputs.	Own
SearchFileByPoint	JavaScript	Searched for the file associated with the daily rainfall depth from a database, using the geographical coordinates.	Own
teechart	JavaScript	Charting library that plots graphs for all compatible browsers in native JavaScript format, using the HTML5 Canvas element.	Steema (2015)
Google Maps Api	JavaScript	Script with a variety of services, enabling the use of maps, geocoding, places, and other content from Google in web pages or applications.	Google (2015)
JQuery	JavaScript	JavaScript library that enables HTML document traversal and manipulation, event handling, animation, and use of Ajax with an API that works across a multitude of browsers.	JQuery (2016)
EstEf	Python	Transfers input data on household and the rainfall file path to execute in sequence DmdGen, DispGen, and EfAlm.m files.	Own
ProjectPoint	MatLab	Converts coordinates from geographical to UTM (Universal Transverse Mercator) projection and vice versa.	Own
EstEf	MatLab	Estimates annual efficiency from equation (1).	Own
EstDef	MatLab	Calculates daily deficit in water saving potential from equation (2).	Own
Almdiario	MatLab	Estimates and saves the daily saved water volume from equation (3).	Own
DispGen	MatLab	Calculates daily available water volume from equation (4).	Own
DmdGen	MatLab	Estimates daily water demand from equation (5)	Own
EfAlm.m	MatLab	Provides the matrix of annual efficiency, vector of tank sizes, and standard deviation of the efficiency, assuming that standard deviation tends towards a constant as tank size increases.	Own
ProbSeries	MatLab	Provides a vector of non-exceedance probabilities for each tank size value from a beta probability density function.	Own

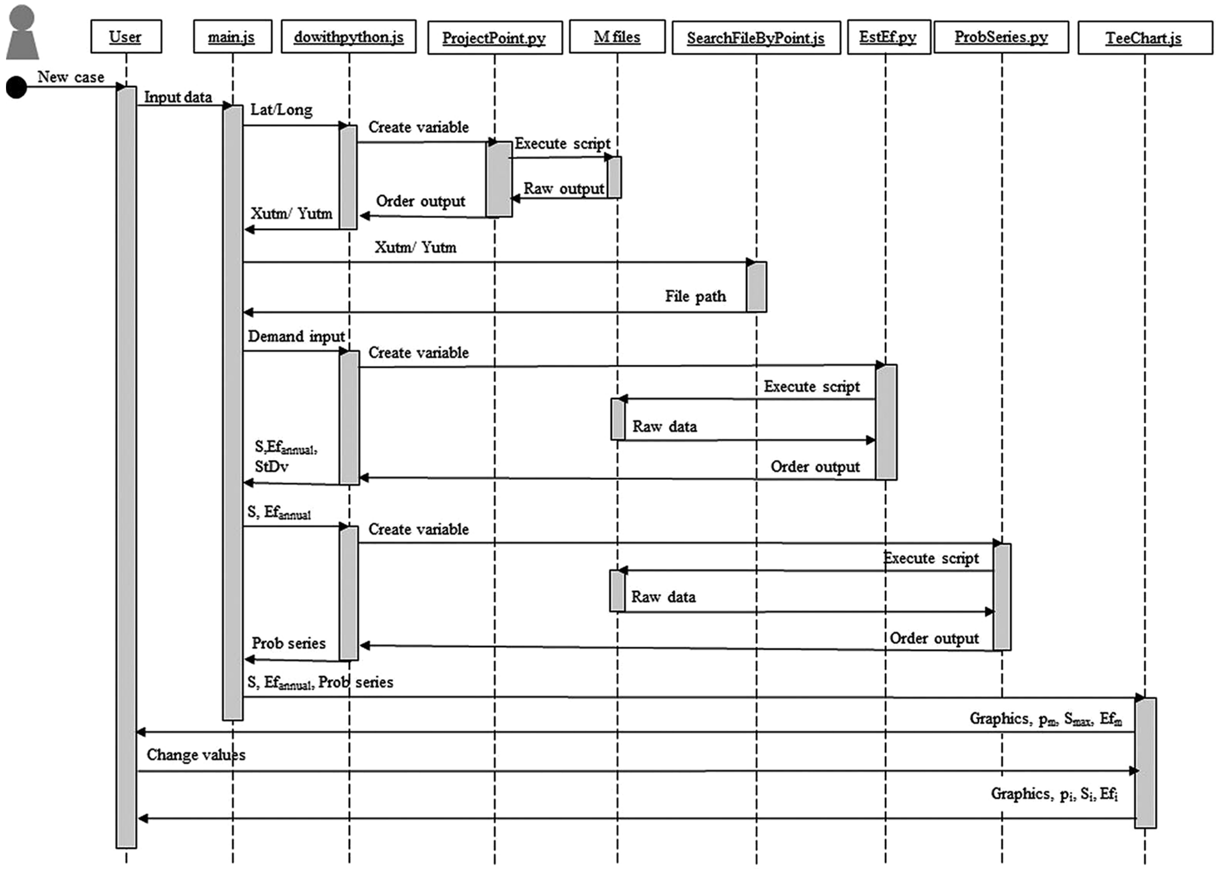


Fig. 6. Sequence UML diagram of the web application.

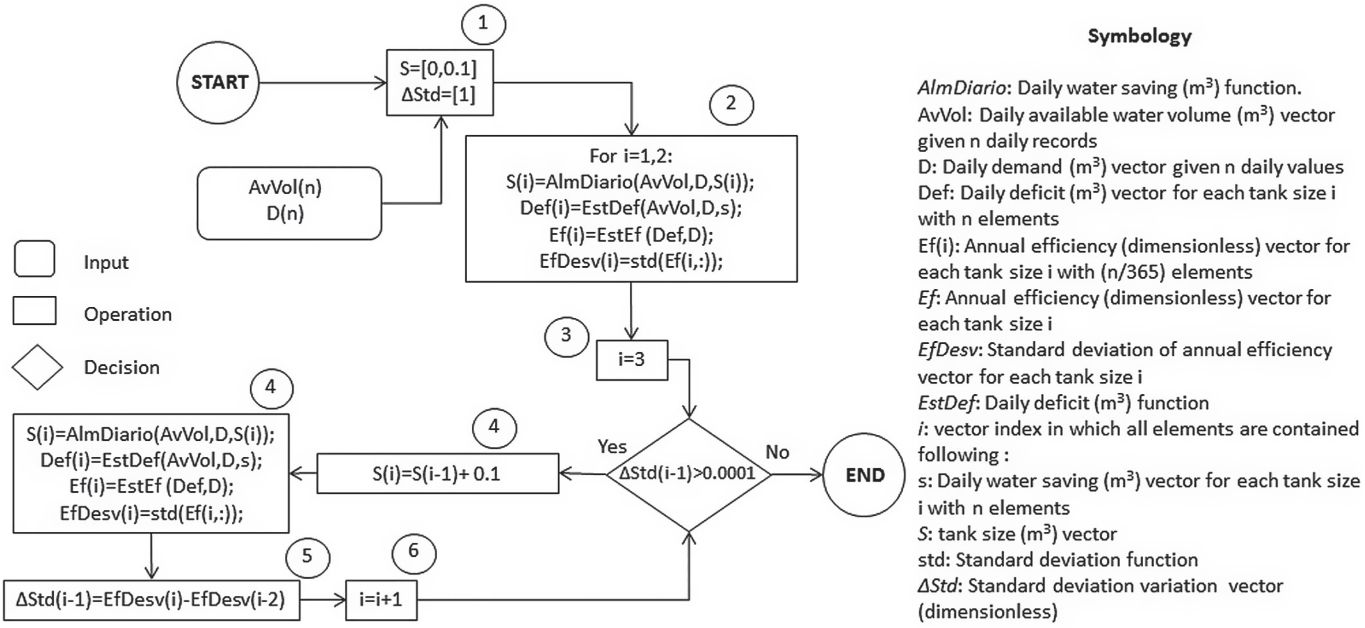


Fig. 7. Flow chart of the module EfAlm.m.

main.js, the user may interact with graphics using the TeeChart.js module.

3. Results and discussion

The interface corresponding to the web application (Fig. 8) for estimating the tank size of RHSs, based on the previously created UML sequence diagram, is available at http://redlerma/apps/cosechadelluvia.uaemex.mx. First of all, it is possible to see three parts, the conceptual model of the RHS, the map for locating the case study and the input data with standard values, which users are allowed to either keep or modify (number of inhabitants, type of catchment surface and its area, runoff coefficient, and daily *per capita* domestic water demand). After executing the "storage estimation" button, results are shown as scalar values for average daily rainfall depth and its standard deviation and as graphical representation for the series obtained during the efficiency simulation. The user may also select either an efficiency series from the available tank size vector and the efficiency value as a function of the non-exceedance probability. In other words, given a tank size, high non-exceedance probabilities provide efficiency values from a "conservative" approach, while low non-exceedance probabilities depict an "optimist" approach on efficiency values.

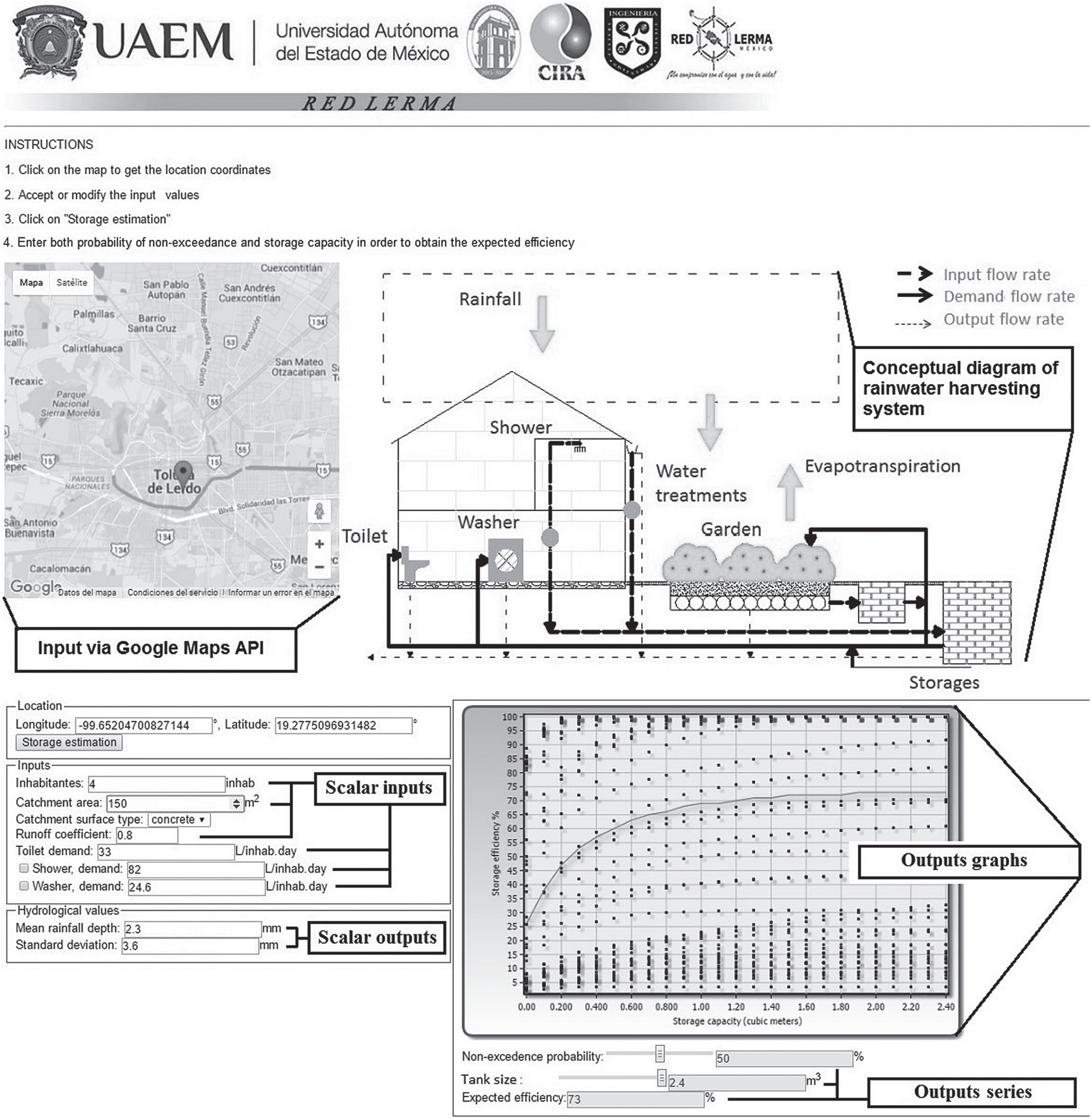
The web application was validated for the selected case studies (Ecatepec, Toluca, and Ixtapan de la Sal) chosen to represent the urban areas of the State of Mexico with the highest population densities per rainfall regime. The annual mean rainfall depths estimated for Ecatepec, Toluca and Ixtapan de la Sal were 704, 874 and 1127 mm respectively. Nevertheless, greater annual mean rainfall depths are associated with greater variability, as represented by their standard deviation: 73, 98 and 149 mm. Daily average rainfall depth was 1.9 mm in Ecatepec (standard deviation = 3.0 mm), 2.4 mm in Toluca (standard deviation = 3.7 mm), and 3.2 mm in Ixtapan de la Sal (standard deviation = 6.4 mm).

The provided results by the web application (Table 3) show the maximum tank sizes and annual efficiency values. Additional increases from the maximum tank sizes have non-significant variations on annual efficiencies, as the trend of standard deviation of simulated annual efficiencies in function of the tank size demonstrate in Fig. 9. There, the standard deviation increase nearly proportionally up to a tank size of 0.3 m^3 in all cases. Beyond this point, standard deviation, which ranges from 25 to 42% of annual efficiency, tend towards a constant, or even lower values in some cases.

Maximum tank sizes were observed to range from 1.2 to 5.3 m^3. However, in the case of Toluca, for a surface catchment area of 200 m^2, a greater tank size was observed (5.3 m^3) in relation with Ixtapan de la Sal (5.0 m^3), which has a higher level of rainfall. Accordingly, it may be inferred that regimes with lower rainfall variations allow for greater values of annual efficiency to be reached given similar tank sizes.

With respect to the expected annual efficiency, values between 13 and 99% were found given average rainfall conditions. For wetter conditions, the expected minimum annual efficiency in the supply was 87% (in Ecatepec), while in drier conditions, the expected maximum annual efficiency was 80% (in Toluca). The annual efficiencies were estimated by a beta probability density function, resulting in high values for the determination coefficient ($R^2 > 0.92$) and an acceptable level of significance (p-value < 0.05). In the majority of cases (Fig. 10), the best correlation between estimated and simulated annual efficiency was found for tank sizes of less than 0.7 m^3, with the exception of Toluca, in which this was true for tank sizes of greater than 5.0 m^3. In addition, Fig. 11 present the daily cumulative rainfall for the wet, average, and dry years considered to be representative of each case study. In general, the greatest accumulation of rainfall is recorded between days 150 and 270 (from June to September),. Therefore, it is possible to infer that during dry years, efficiency would increase significantly if this were the only period to be considered.

In the selected case studies, annual efficiency in the water supply increased, overall, in areas with higher annual averages rainfall depths. However, lower variation in rainfall (represented by the standard deviation) also resulted in higher tank sizes and increases in the annual efficiency of the supply. In this sense, Ixtapan de la Sal, with half the tank size of Ecatepec, presented annual



INSTRUCTIONS

1. Click on the map to get the location coordinates
2. Accept or modify the input values
3. Click on "Storage estimation"
4. Enter both probability of non-exceedance and storage capacity in order to obtain the expected efficiency

Location

Longitude: -99.65204700827144°, Latitude: 19.2775096931482°

Inputs

Inhabitantes: 4 inhab
Catchment area: 150 m^2
Catchment surface type: concrete
Runoff coefficient: 0.8
Toilet demand: 33 L/inhab.day
☐ Shower, demand: 82 L/inhab.day
☐ Washer, demand: 24.6 L/inhab.day

Hydrological values

Mean rainfall depth: 2.3 mm
Standard deviation: 3.6 mm

Non-excedence probability: 50 %
Tank size : 2.4 m^3
Expected efficiency: 73 %

Fig. 8. Interface of DSS for the tank size estimation in a rainwater harvesting system.

efficiency values up to six times higher (84%) in terms of the potential water savings under average conditions. Meanwhile, in Toluca the largest tank size (5.3 m^3) is observed to reach an annual efficiency of 70%, even in driest conditions. For average conditions and a catchment surface area of 200 m^2, it is possible to observe an annual potential water savings of 38,200, 41,400, and 46,500 L per houseold in Ecatepec, Ixtapan de la Sal, and Toluca, respectively.

Despite a RHS focuses on water resources conservation for sustainable developments, there are also other social benefits. Among those benefits, it is possible to point out flood risk mitigation in urban areas and money saving potentials due to water supply services tariff. Due to results in monetary terms are hard to follow because of both currency fluctuations (i.e. devaluation) and hidden costs, for instance subsidies; Table 3 also shows likely annual man-hours savings based on a monthly water supply service tariff of 7.294 minimum salaries regarding: a) tariff for medium household in the State of Mexico (L.E.M., 2015) and; b) workday about 8 h per day. A range from 22 to 166 man-hours for a mean year depicts up to 24% of the annual spending on water supply service.

Table 3
Data outputs of the web application for the study cases.

Parameter	Study case	Catchment surface (m^2)		
		90	150	200
Demand[a] (m^3/day)	Ecatepec	0.165		
	Toluca	0.132		
	Ixtapan	0.132		
Maximum tank size (m^3)	Ecatepec	2.3	2.4	2.9
	Toluca	1.8	2.4	5.3
	Ixtapan	1.2	4.1	5.0
Efficiency for wet year (%)	Ecatepec	87–98	95–99	96–99
	Toluca	94–99	97–100	100–100
	Ixtapan	95–99	98–100	99–100
Efficiency for mean year (%)	Ecatepec	13–64	30–81	41–86
	Toluca	28–80	49–89	94–99
	Ixtapan	39–84	64–92	76–96
Efficiency for dry year (%)	Ecatepec	0.4–3.2	2–10	4.7–18
	Toluca	1.6–9.1	7.5–24	70–80
	Ixtapan	4.6–17	20–42	31–56
Man-hour savings saving Wet year (hr)	Ecatepec	146–165	160–166	161–166
	Toluca	158–166	163–168	168–168
	Ixtapan	160–166	165–168	166–168
Man-hour saving Mean year (hr)	Ecatepec	22–108	50–136	69–145
	Toluca	47–135	82–150	158–166
	Ixtapan	66–141	108–155	128–161
Man-hour saving Dry year (hr)	Ecatepec	0.7–5.4	3.4–17	7.9–30
	Toluca	2.7–15	13–40	118–135
	Ixtapan	7.7–29	34–71	52–94

[a] Daily demand: Product of water demand for W.C. [L/hab/day] and population density [hab/household].

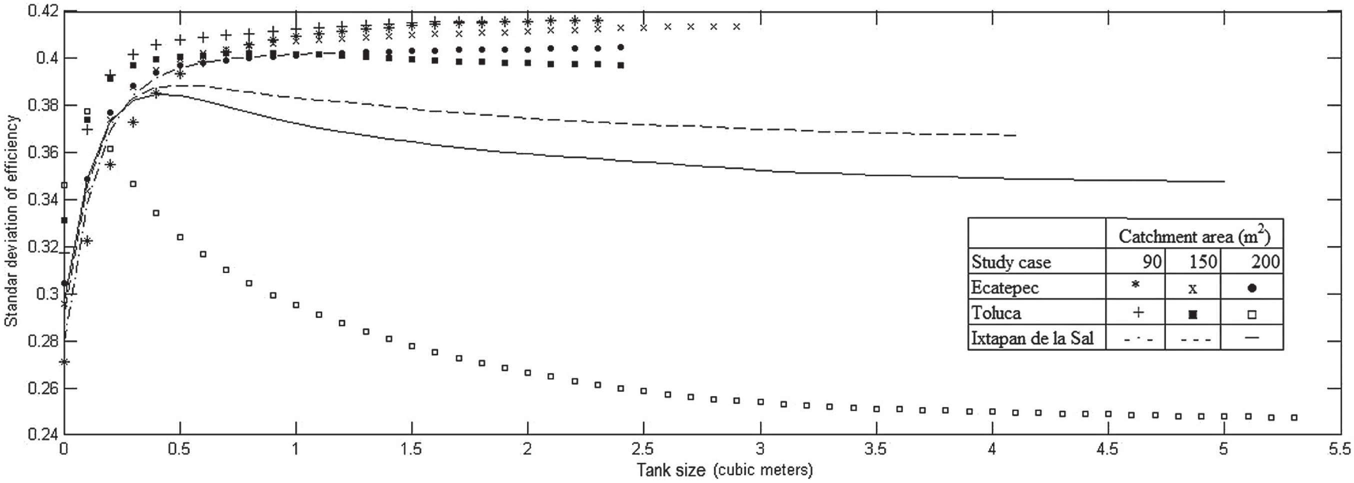


Fig. 9. Trend in standard deviation of efficiency as a function of increases in tank size.

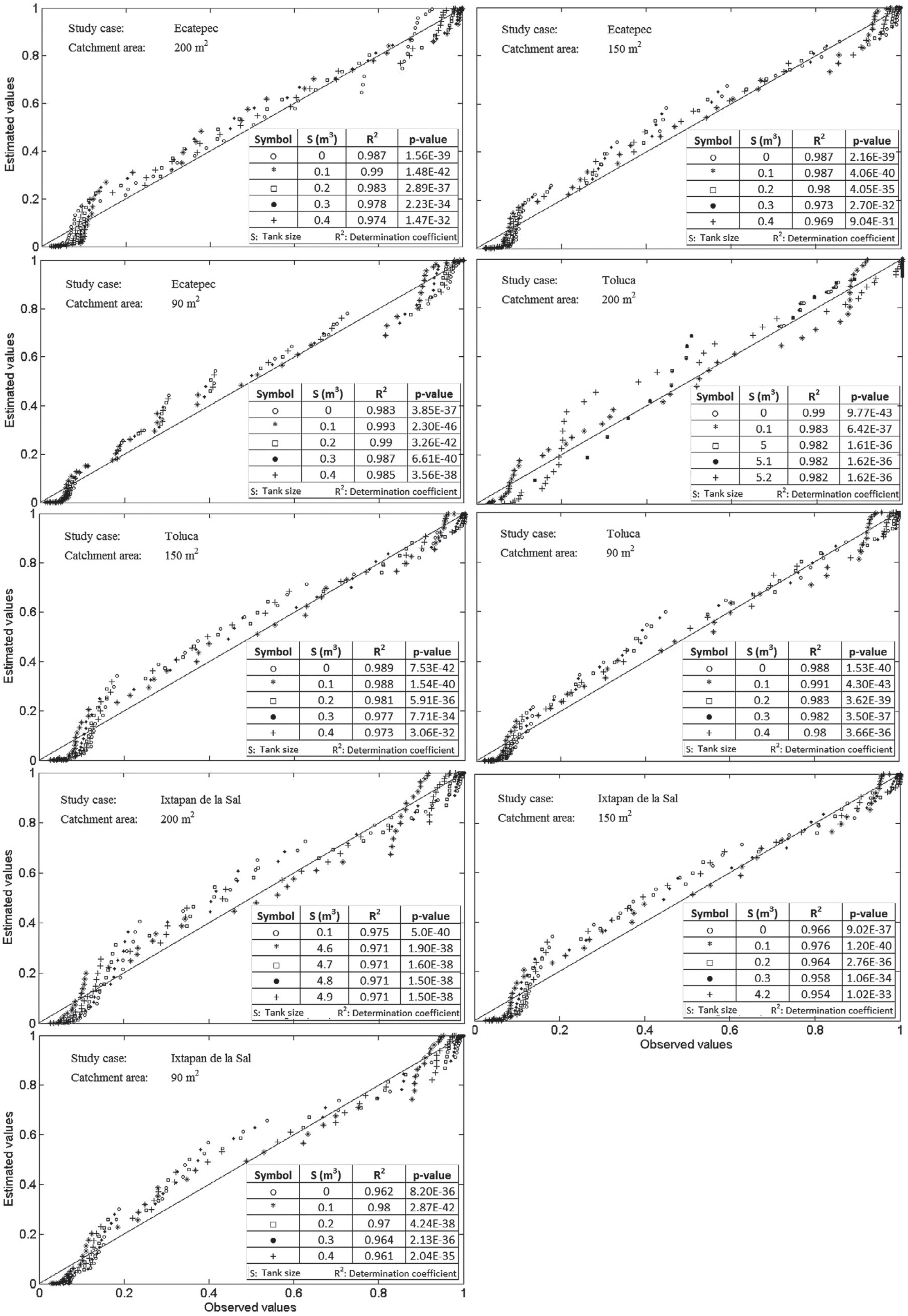
4. Conclusions

The Decision Support System DSS developed and validated in this study was constructed following a four-stage method of software development in order to: a) identify variables that influence rainwater harvesting systems (RHS) and b) delimit the functional relationships between these variables in order to create a support tool for decision making that would determine the optimal tank size regarding a non-exceedance probability.

A basic version of a web application was generated with the objective of requiring a minimal amount of input data. First of all, the format and timestep of the variables involved were identified. Different components of the system, such as number of inhabitants, catchment surface area, runoff coefficient, and water demand for domestic use, may use default values. Daily rainfall values may also be obtained from an external database, based on the geographic coordinates of the site where the RHS will be placed. Therefore, this application allows the end user to obtain an optimal dimensioning of storage tanks, solely by providing their future location.

In taking into consideration the potential combinations of the variables of RHSs, the developed web application provides an interval of location-specific values of tank sizes. The simulations of annual efficiency, based on the daily mass balance method, are performed in real time in the web application in order to determine the tank size threshold when the variation of simulated annual efficiency tends towards a constant. This variation was depicted in terms of the simulated annual efficiency standard deviation calculated for all of the available daily rainfall records (which also are provided by an external database). In this way, the design of RHSs may be optimal and not strictly limited to the use of arbitrary or predetermined values for storage size (commercial tanks).

The case studies were limited to the State of Mexico due to the geographical limits of the pre-processed rainfall records used in this study. However, the use of this tool may be expanded to the



Study case: Ecatepec
Catchment area: 200 m^2

Symbol	S (m^3)	R^2	p-value
○	0	0.987	1.56E-39
*	0.1	0.99	1.48E-42
□	0.2	0.983	2.89E-37
●	0.3	0.978	2.23E-34
+	0.4	0.974	1.47E-32

S: Tank size R^2: Determination coefficient

Study case: Ecatepec
Catchment area: 150 m^2

Symbol	S (m^3)	R^2	p-value
○	0	0.987	2.16E-39
*	0.1	0.987	4.06E-40
□	0.2	0.98	4.05E-35
●	0.3	0.973	2.70E-32
+	0.4	0.969	9.04E-31

S: Tank size R^2: Determination coefficient

Study case: Ecatepec
Catchment area: 90 m^2

Symbol	S (m^3)	R^2	p-value
○	0	0.983	3.85E-37
*	0.1	0.993	2.30E-46
□	0.2	0.99	3.26E-42
●	0.3	0.987	6.61E-40
+	0.4	0.985	3.56E-38

S: Tank size R^2: Determination coefficient

Study case: Toluca
Catchment area: 200 m^2

Symbol	S (m^3)	R^2	p-value
○	0	0.99	9.77E-43
*	0.1	0.983	6.42E-37
□	5	0.982	1.61E-36
●	5.1	0.982	1.62E-36
+	5.2	0.982	1.62E-36

S: Tank size R^2: Determination coefficient

Study case: Toluca
Catchment area: 150 m^2

Symbol	S (m^3)	R^2	p-value
○	0	0.989	7.53E-42
*	0.1	0.988	1.54E-40
□	0.2	0.981	5.91E-36
●	0.3	0.977	7.71E-34
+	0.4	0.973	3.06E-32

S: Tank size R^2: Determination coefficient

Study case: Toluca
Catchment area: 90 m^2

Symbol	S (m^3)	R^2	p-value
○	0	0.988	1.53E-40
*	0.1	0.991	4.30E-43
□	0.2	0.983	3.62E-39
●	0.3	0.982	3.50E-37
+	0.4	0.98	3.66E-36

S: Tank size R^2: Determination coefficient

Study case: Ixtapan de la Sal
Catchment area: 200 m^2

Symbol	S (m^3)	R^2	p-value
○	0.1	0.975	5.0E-40
*	4.6	0.971	1.90E-38
□	4.7	0.971	1.60E-38
●	4.8	0.971	1.50E-38
+	4.9	0.971	1.50E-38

S: Tank size R^2: Determination coefficient

Study case: Ixtapan de la Sal
Catchment area: 150 m^2

Symbol	S (m^3)	R^2	p-value
○	0	0.966	9.02E-37
*	0.1	0.976	1.20E-40
□	0.2	0.964	2.76E-36
●	0.3	0.958	1.06E-34
+	4.2	0.954	1.02E-33

S: Tank size R^2: Determination coefficient

Study case: Ixtapan de la Sal
Catchment area: 90 m^2

Symbol	S (m^3)	R^2	p-value
○	0	0.962	8.20E-36
*	0.1	0.98	2.87E-42
□	0.2	0.97	4.24E-38
●	0.3	0.964	2.13E-36
+	0.4	0.961	2.04E-35

S: Tank size R^2: Determination coefficient

Fig. 10. Correlation between estimated and simulated efficiency.

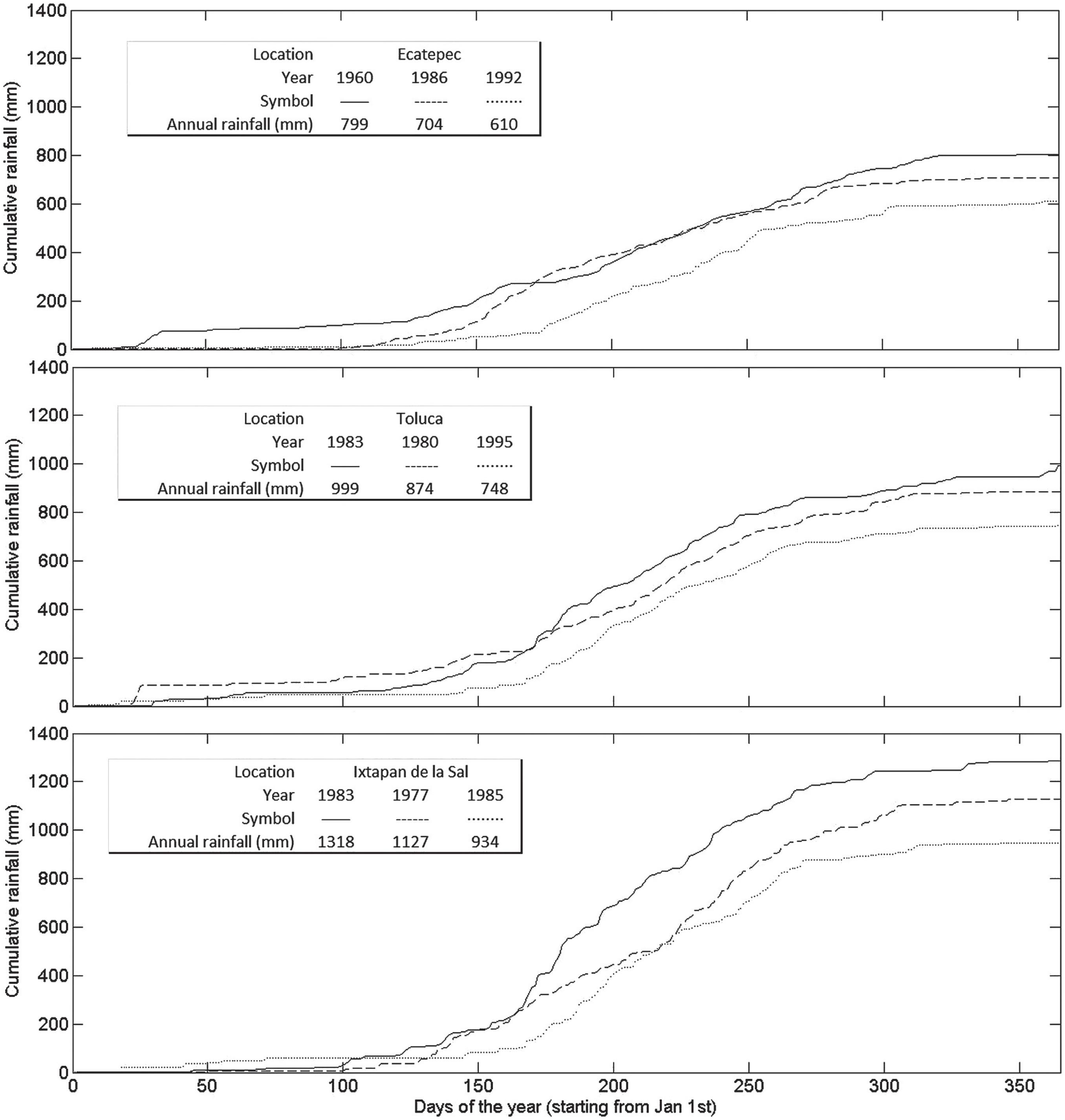


Fig. 11. Cumulative rainfall pattern for selected years.

national or even international scale, as long as spatial-temporal records on daily rainfall depth are available in external databases. Likewise, future versions of the web application are expected to include additional storage tanks in order to model water demand for the irrigation of green areas.

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