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The establishment of integrated water resources management based on emergy accounting

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ABSTRACT

With modules developed in an informatics package for geographic information systems (GIS), the present work calculates the emergy of groundwater and the inter-annual variation in emergy of surface water resources in basins that encompass the metropolitan areas of Toluca and Monterrey, Mexico; that is, Upper Course of the Lerma River (UCLR) and the Santa Catarina River (SCR) basin, respectively. In addition, a criterion has been found to identify the intensive exploitation of aquifers. This allows for considering those volumes as non-renewable resources, when applicable, in processes to define integrated water resources management.

The transformity weighted mean of water resources due to chemical potential energy in the SCR basin (9.32E + 06 sej/J for surface water and 6.47E + 06 sej/J for groundwater) was greater than in the UCLR basin (5.75E + 05 sej/J for surface water and 2.83E + 05 sej/J for groundwater). Nevertheless, based on the analysis of the variation in emergy, some strategies were identified to improve the efficiency of the joint management of water resources. Standing out among these is the determination of a monthly variability in the volumes of water provided, making it possible to observe a decrease in emergy per unit volume in the SCR basin and an increase in the percentage of renewable resources in the UCLR basin.

1. Introduction

In the search to define sustainable water management processes, it is increasingly important to identify the characteristics of water supply sources. In addition, increased human activity has become the primary agent for causing disturbances in the resource, having quantitatively and qualitatively altered the natural balance of hydrological processes.

Integrated water resources management (IWRM) emphasizes the importance of including the management of both surface water and groundwater in water plans at national and basin levels. It also builds communication bridges among experts, technicians, decision-makers, operating entities and users. Without this communication, it is difficult to understand the processes, environmental consequences and socioeconomics involved in the interactions between surface water and groundwater (Cap-Net, 2010). Management tools need to be developed in such a way that they: (a) help governmental agencies to more realistically analyze the quantity of water available and the amount used in their regions and (b) consider the water resource as an economic good in the broadest sense of the concept, rather than an exclusively monetary terms (Martínez et al., 2011; Fattahi and Fayyaz, 2010; Xiaoqin, 2009).

Furthermore, although the concept of the economic value of water is accepted by the international community, the methods to calculate it mostly focus on the quantification of benefits and services, and rarely consider the natural value of water (Chen et al., 2009). This omission can create a false perception about the value of water, a decrease in the quality of the service and a willingness on the part of users to pay for it, as well as operational inefficiency and deterioration of the supply infrastructure (UN WATER Report, 2012).

Pulselli et al. (2011a) have described the main differences between evaluate the nature value, in this case of water, as an economic good and as a representation of the work done by nature to

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provide a service. While the economic measure of water value can be estimated through the human wellbeing provided by the ecosystem services – remaining as an user-side approach – the intrinsic value needs an evaluation from a donnor-side approach, even if the total work that support a system is not converted into ecosystem services (Pulselli et al., 2011a; Vassallo et al., 2013). In this sense, the emergy theory provides a perspective with a donnor-side approach to evaluate, in an integrated manner, the value of natural resources and relationships between nature and society (Cai et al., 2004).

The relationship between the emergy flow that feeds an ecosystem and the services it provides is not necessarily directly proportional. There is the case where the resources processed by the ecosystem are translated into a loss of utility for humans (Pulselli et al., 2011a). This is the case of water resources, which increase its emergy because of both sediments tansport and the pollutants discharge, and loss utility for human in form of urban and agriculture uses.

Surface water, a natural consumable, has been evaluated in terms of emergy by a large number of studies. For example, pressure on water resources caused by socioeconomic systems in several countries- such as Brazil, China, Ecuador, Italy, Japan and the United States, among others- has been evaluated by Odum and Arding (1991), Ulgiati et al. (1994), Odum (1996, 2000) and Jiang et al. (2008). To a lesser degree, surface water has been studied by Pulselli et al. (2011b), who analyzed the variation in emergy throughout surface water streams in a basin, and for Mellino et al. (2013) who evaluate the water as renewable resource with a GIS- approach.

Although there are fewer studies of groundwater, it has also been evaluated by Buenfil (2001) and Lv and Wu (2009) in terms of emergy, as well as by Brown et al. (2010) for proposals regarding payment for water services. Water, which is considered a renewable resource, also continues to be an essential element in the analysis of emergy for irrigation (Lu et al., 2010; Chen et al., 2011), construction (Srinivasan et al., 2011) and urbanization activities (Zhang et al., 2009), among others.

The initial argument to classify water resources as renewable is to consider water as a finite element on Earth which is constantly being renewed, thanks to solar energy, through the hydrological cycle. Nevertheless, at a local scale, water is extinguishable because of its vulnerability and storage capacity (Sustainable Resource Unit A2, 2002). In places where groundwater is used, and especially in arid regions, a permanent reduction can be seen in the reserves of water bodies, which is known as water "mining" (Foster and Loucks, 2006). In these cases, some authors consider water resources as non-renewable (El-Sadek, 2010; Kajenthira et al., 2012) in regards to water management.

With some natural resources, such as oil and wind, their renewability is not a matter for discussion. Actually, oil is clearly classified as non-renewable because of the long amount of time it takes for nature to transform it from fossil bodies. On the other hand, wind is considered renewable without question. While for water, the threshold at which it becomes a non-renewable resource is not yet clear.

The present work, with modules developed in an informatics package for geographic information systems (GIS), calculates the inter-annual variation in the emergy value of surface water resources in basins that encompass two of the largest metropolitan areas in Mexico – Toluca and Monterrey – regions whose climates define their water regimes differently. In addition, based on the calculation of emergy, a criterion has been found to identify the intensive aquifer exploitation, in which those volumes are considered non-renewable resources in processes to define strategies to improve the efficiency in the water use within an integrated management of water resources.

2. Basic concepts

Emergy is conceived of as the available energy (exergy) needed, directly or indirectly, to create or improve the characteristics of a product or service; measured and analyzed in common solar energy units (Odum, 1996). This theory attempts to assign the scientific value to ecological and economic products and services based on a theory of the flow of energy in the ecology of a system and the relationship with its survival (Hau and Bakshi, 2004). In emergy accounting, various forms of energy are translated into solar energy equivalent, or solar emergy, by way of a conversion factor (transformity) that reflects the energy's qualitative value. Through multiplying the inputs and outputs by their respective transformities, the emergy amount of each resource, service and corresponding product can be calculated (Lv and Wu, 2009). If the flow is evaluated as mass, then it is converted to emergy using a *specific emergy* – ratio or solar emergy to mass sej/g – (Brown et al., 2010). In general, the quantity of equivalent solar energy per unit product – expressed in sej/J or other unit – can be defined as unit emergy value UEV (Pulselli et al., 2011b).

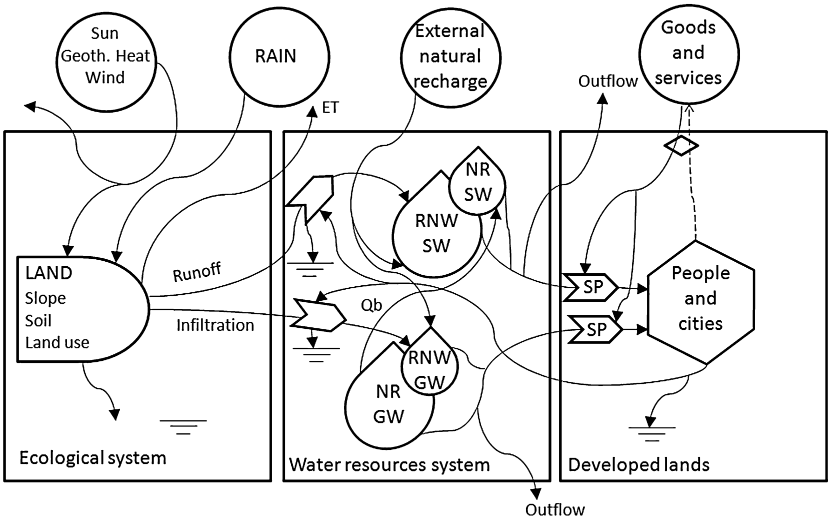
2.1. Emergy of water resources

In the case of water, the emergy value can be provided by both the chemical potential energy, which is a crucial source of biological production (Chen et al., 2009), and the geopotential energy–the work that water running off the landscape can do as it falls from higher elevation to lower elevations (Brown et al., 2010). The chemical potential energy reflects the qualitative status of water resources, such as the purity of water relative to seawater (Brown et al., 2010). It is calculated based on Gibbs free energy, taking into account the concentrations of total dissolved solids (TDS) (Odum, 1996). Although calculating the chemical potential energy of water based only on TDS omits other important parameters that define the quality of water for human consumption – such as chemical and biological oxygen demands – it can be used for an initial estimate of the emergy value of a resource. The addition of other parameters can be observed by the energy needed to recover the status of the water before the inclusion of contaminant loads. This energy depends on water treatment processes and has been calculated by a variety of studies, such as those conducted by Siracusa and La Rosa (2006), Arias and Brown (2009), Vassallo et al. (2009), Zhou et al. (2009), Zhang et al. (2010) and Taskhiri et al. (2011).

The emergy that corresponds to surface water resources in a basin is spatially and temporally variable, in part due to the differences in water quality found throughout its rivers. Low values for the presence of total dissolved solids can be observed in the upper sections, while high values can be found in the lower sections due to the effect of sediment transport or discharges from anthropogenic activities. Likewise, at a single point along the river, the water quality changes over the course of a year according to the volume of water flowing through its cross-section. Therefore, in general, lower concentrations of total dissolved solids are found during rainy months due to the effects of dilution.

2.2. Non-renewable water resources

In the emergy accounting, the use of diagrams has made it possible to establish rules for the presentation of emergy flows in a known system. This is referred to as energy circuit language (Brown, 2004). Depending on their characteristics, emergy flows are classified as renewable or non-renewable natural resources (Siche et al., 2010). This classification enables evaluating the sustainability of a system using indicators such as percentage of renewable resources, which is defined as the relationship between



RNW SW: Renewable surface water
NR SW: Non-renewable surface water
RNW GW: Renewable groundwater
NR GW: Non-renewable groundwater

ET: Evapotranspiration
Qb: Base flow
SP: Supply processes
NR GW: Non-renewable groundwater

Fig. 1. Emergy diagram of the water resource systems under study.

the emergy flow of renewable resources and the total emergy in a system (Odum, 1996). The highest values for this indicator represent long-term sustainable processes.

Fig. 1 shows a diagram where the water resources system is represented between the ecological system and the developed lands. This diagram, based on those constructed by Jiang et al. (2008), Brown et al. (2010), Pulselli et al. (2011b) and Liu et al. (2013) highlights the processes feeded by rain, sun, wind and geothermal energy after pass across the land, whose physiographic features splits the water flow in runoff and infiltration toward the emergy storages at first, and evapotranspiration toward out of water resource system boundary. In addition, it is possible to observe two kind of storage associated with renewable and non-renewable resources respectively.

In order to identify the renewable resources from those who are not, the FAO (2003) defines renewable water resources as "the average annual flow of rivers and recharge of aquifers generated from endogenous precipitation." Although water certainly undergoes a process of natural cleansing and maintains a dynamic balance over time thanks to hydrological process, human intervention has resulted in changes not only in the quantity of surface and groundwater reserves but also in the quality of the resource. Especially in the case of deep aquifers, use has been made of bodies of water with recharge rates ranging from hundreds to thousands of years (Foster et al., 2006; Margat et al., 2006). Therefore, in terms of the rate of recharge, the concept of non-renewability of water resources is primarily associated with groundwater.

Once the characteristic of renewable water resources is defined, the question is posed as to how much of the water used for human activities is renewable. To this end, two of the criteria that can define groundwater resources as non-renewable are (Vrba and Lipponen, 2007): (a) when the annual mean recharge is less than 0.1% of the stored volume and (b) when the exploitation of the groundwater has a significant impact on neighbouring systems or on recharged groundwater bodies. Given the second criterion, the intervention of exploitation undoubtedly provokes problems of reductions in groundwater levels.

Vrba and Lipponen (2007) identify situations that reflect the problem of reductions in groundwater levels (Table 1). Nevertheless, the identification of some of those criteria presents certain disadvantages. For example, it is not likely that a site would have an adequate network to monitor the quality of groundwater or that technical studies would exist to validate that differential land subsidence is solely due to the groundwater depletion. Therefore, to address this problem, indicators exist that show the trend in the piezometric level of an aquifer, such as the filling index (FI), which represents the aquifer's situation with respect to maximum and minimum variations during a historical period of years (Pernía et al., 2005; Vrba and Lipponen, 2007; Van Camp et al., 2010).

Non-renewable groundwater can be also present in surface water in the form of base flow. Its estimating and separation, if is necessary, can be graphically or analytically performed, such as in the case of recession curves and frequency analyses (Chapman, 1991).

3. Materials and methods

The method developed for this work (Fig. 2) uses two perspectives in the emergy accounting with respect to the origin of water resources. The first involves surface water and highlights the influence of the inter-annual variability in precipitation and runoff on emergy and transformity values. The second perspective promotes the conservation of groundwater reserves through the use of a criterion to classify them as non-renewable resources.

These approaches are based on the recharge rate and residence times of water body systems. The inter-annual variability of recharge is generally more significant for surface water than for groundwater due to the relatively short residence times in the system – the travel time can be measured in minutes, hours or days – while for groundwater it can be reflected in terms of months and even years, depending on the porosity and depth of the soil, and the geological structures in place.

The purpose of this procedure is to generate basic information (temporal and spatial variations in emergy and the volume of renewable resources) to support possible strategies for the joint management of water resources. While the temporal and spatial variation in emergy enables locating likely supply sources by identifying the water resources with the lowest transformity, the

Table 1
Elements for the identification of an aquifer impacted by the intensive exploitation (Vrba y Lipponen, 2007).

Element	Description
Areas with high density production of wells	A strong depletion of the groundwater associated with increased pumping costs or loss of wetlands or reducing yields of wells may indicate groundwater depletion in areas where many wells are exploiting an aquifer. Two alternatives to identify the depletion of the water are: (a) detection from network monitoring wells gradual persistent negative trend in water level or, (b) comparing the level of groundwater in wells drilled at different times.
Changes in the base flow	The rivers and other surface water bodies may be formed by a significant proportion of groundwater flow from the base. A drastic reduction of this flow may be associated with groundwater depletion. In this case the stream flow monitoring is important and necessary.
Change in the pattern of groundwater quality	Although the physicochemical properties of water can vary throughout the aquifer, in normal operating conditions, no drastic changes are expected in quality. Thus, changes in the age and origin of groundwater in specific locations in the aquifer can be a sign of groundwater depletion.
Differential settlement of ground	In some locations, groundwater exploitation from thick aquitard systems has been accompanied by significant differential land subsidence. Subsidence in this situation can be considered as an indirect indicator of unsustainable exploitation of groundwater.

percentage of renewable resources reflects the conservation of water resources through the proportion of renewable resources versus non-renewable and imported resources from others basins.

In addition, it is worth mentioning that the geomatic processes shown in Fig. 2 (Phases 1 through 5) can be conducted using two modules developed for this work, with the Idrisi geographic information systems platform (Eastman, 2006).

3.1. Module to calculate the emergy of surface water using GIS

This module, whose interface and flow diagram is shown in Fig. 3, is composed of three parts. Similarly to GIS-based model of Mellino et al. (2013), this module requires maps of temperature, digital elevation model and precipitation but, generates distributed models of the reference evapotranspiration, surface runoff and infiltration in a study unit (basin or aquifer) within the first part (Fig. 3a). The reference evapotranspiration is calculated using the Thornthwaite (1948) method and therefore requires images corresponding to the monthly mean temperatures and the mean latitude of the study unit. Infiltration is calculated by algebraically subtracting the reference evapotranspiration images and the potential runoff from the monthly mean precipitation. To construct potential runoff, the module generates the image of a runoff coefficient based on the classification of the topographic

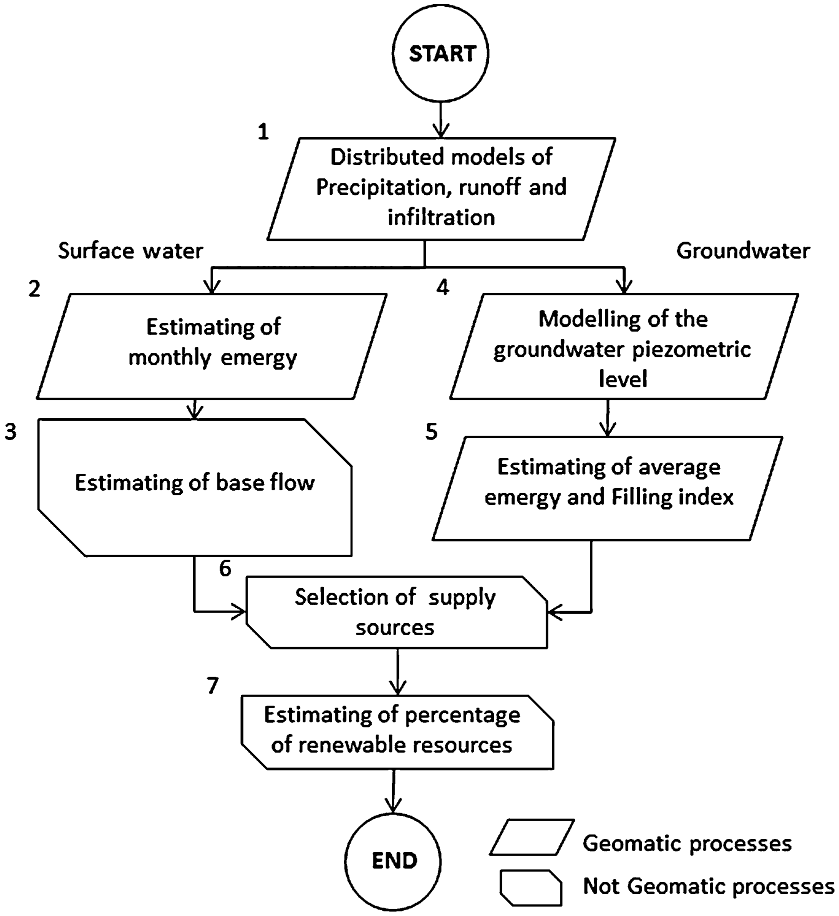
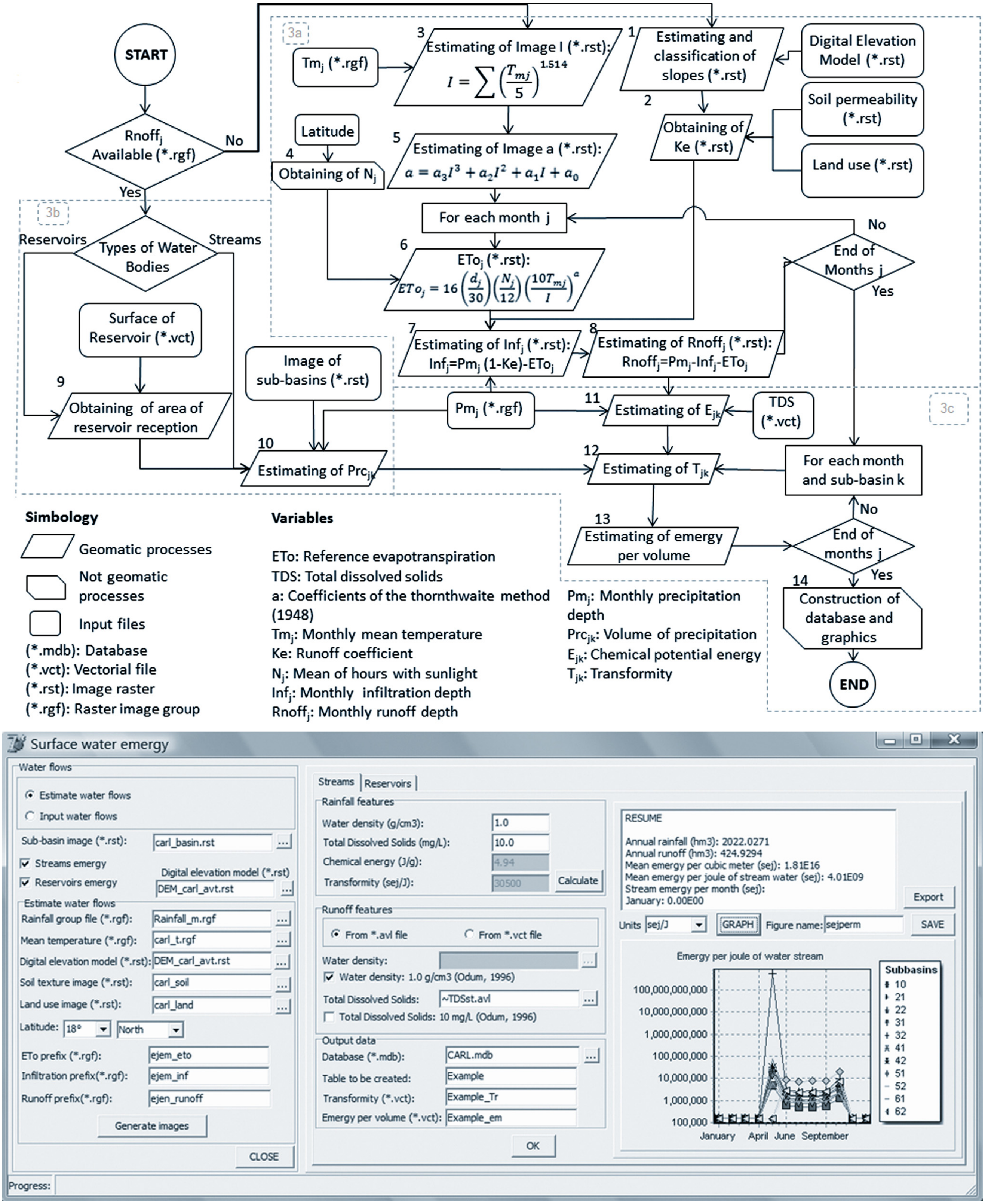


Fig. 2. Emergy analysis for temporal variability and renewability classification of water resources.



Water flows

● Estimate water flows
○ Input water flows

Sub-basin image (*.rst): carl_basin.rst

☑ Streams emergy
☑ Reservoirs emergy

Digital elevation model (*.rst): DEM_carl_avt.rst

Estimate water flows

Rainfall group file (*.rgf): Rainfall_m.rgf
Mean temperature (*.rgf): carl_t.rgf
Digital elevation model (*.rst): DEM_carl_avt.rst
Soil texture image (*.rst): carl_soil
Land use image (*.rst): carl_land
Latitude: 18° North

ETo prefix (*.rgf): ejem_eto
Infiltration prefix(*.rgf): ejem_inf
Runoff prefix(*.rgf): ejen_runoff

Rainfall features

Water density (g/cm3): 1.0
Total Dissolved Solids (mg/L): 10.0
Chemical energy (J/g): 4.94
Transformity (sej/J): 30500

Runoff features

● From *.avl file ○ From *.vct file

Water density:
☑ Water density: 1.0 g/cm3 (Odum, 1996)
Total Dissolved Solids: ~TDSst.avl
☐ Total Dissolved Solids: 10 mg/L (Odum, 1996)

Output data

Database (*.mdb): CARL.mdb
Table to be created: Example
Transformity (*.vct): Example_Tr
Emergy per volume (*.vct): Example_em

RESUME

Annual rainfall (hm3): 2022.0271
Annual runoff (hm3): 424.9294
Mean emergy per cubic meter (sej): 1.81E16
Mean emergy per joule of stream water (sej): 4.01E09
Stream emergy per month (sej):
January: 0.00E00

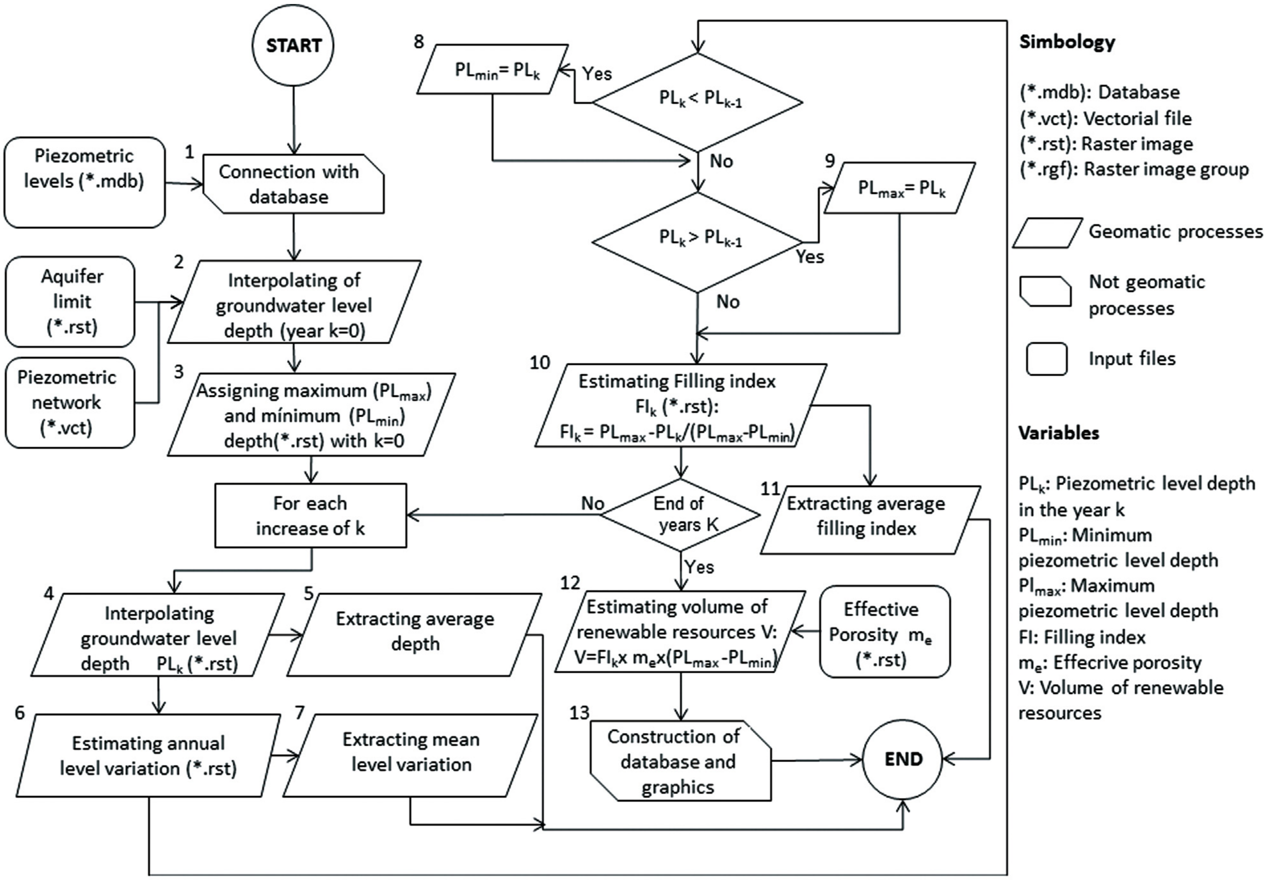
Units sej/J
Figure name: sejperm

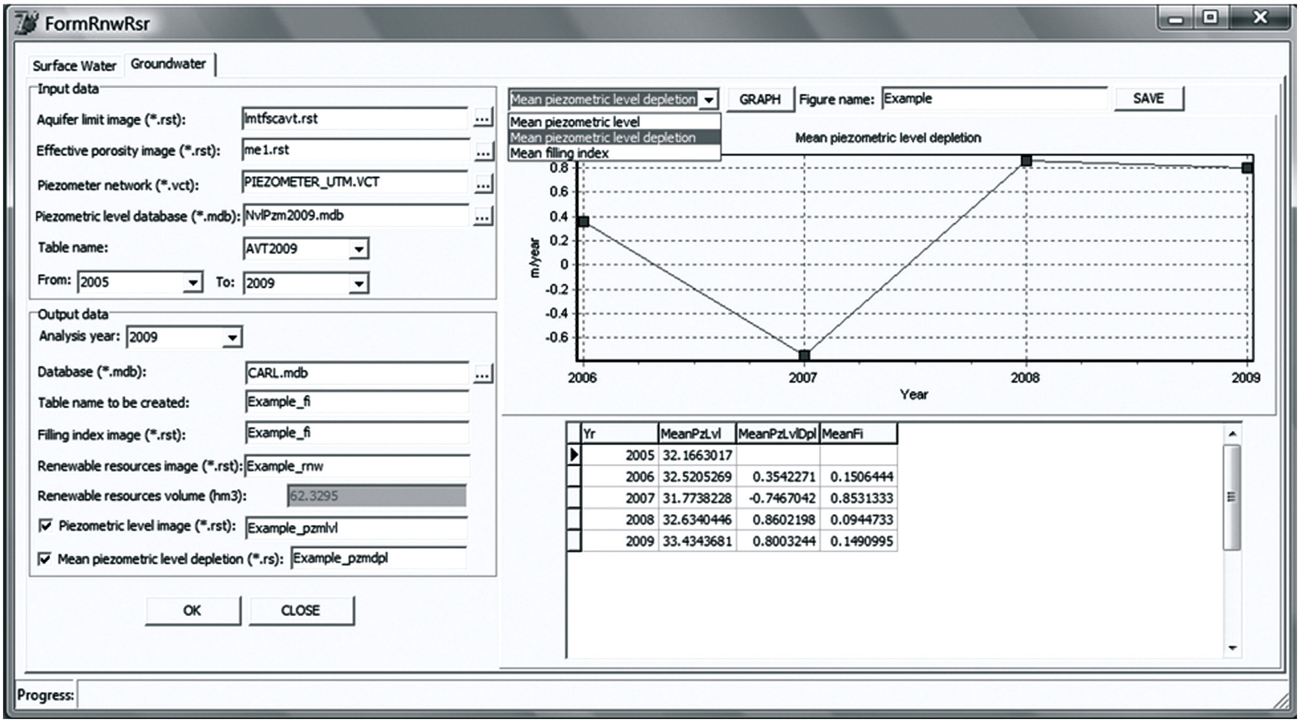
Progress:

Fig. 3. Interface and flow chart for estimating temporarily the surface water resource emergy with GIS.

slope, the permeability of the soil and ground cover and land use (Benítez et al., 1980). Finally, surface runoff is calculated based on the water balance. This information is a useful alternative when distributed models of runoff and infiltration based on more precise and complex methods are not available.

Based on the distributed models, the second part (Fig. 3b) calculates the monthly runoff and infiltration volume associated with





Input data

Aquifer limit image (*.rst): lmtfscavt.rst

Effective porosity image (*.rst): me1.rst

Piezometer network (*.vct): PIEZOMETER_UTM.VCT

Piezometric level database (*.mdb): NvlPzm2009.mdb

Table name: AVT2009

From: 2005 To: 2009

Output data

Analysis year: 2009

Database (*.mdb): CARL.mdb

Table name to be created: Example_fi

Filling index image (*.rst): Example_fi

Renewable resources image (*.rst): Example_rnw

Renewable resources volume (hm3): 62.3295

☑ Piezometric level image (*.rst): Example_pzmlvl

☑ Mean piezometric level depletion (*.rs): Example_pzmdpl

Mean piezometric level depletion

Figure name: Example

Yr	MeanPzLvl	MeanPzLvlDpl	MeanFi
2005	32.1663017		
2006	32.5205269	0.3542271	0.1506444
2007	31.7738228	-0.7467042	0.8531333
2008	32.6340446	0.8602198	0.0944733
2009	33.4343681	0.8003244	0.1490995

Fig. 4. Interface and flow chart to determine filling index and groundwater level variations in an aquifer.

the recharge area of a basin, reservoir or aquifer. To this end, the module requires a digital elevation model to define the corresponding watersheds.

The third part (Fig. 3c) calculates, as the first component of the emergy value, the water chemical potential energy E_{jk} for month j and study unit k (in a basin or sub-basin) based on Equation (1).

$$E_{jk} = \left(\frac{RT}{w}\right) \ln \left[\frac{((1\times10^6) - C_{2jk})}{((1\times10^6) - C_1)}\right] \tag{1}$$

where the gas constant R, the absolute reaction temperature T and the molecular weight of water w are considered constants and are equal to 8.33 J/mol K, 300 K and 18 g/mol, respectively (Odum, 1996). In addition, values C_1 and C_{2jk} are associated with total dissolved solids (TSD) in seawater (C_1 = 35,000 mg/L) and in bodies of surface water (Brown et al., 2010). The information about the C_{2jk} concentration of TDS in water bodies is entered through text files and can be the mean values registered for each study unit.

The transformity T_{jk} of study unit k on month j is calculated based on Equation (2) (Buenfil, 2001):

$$T_{jk} = \frac{(\mathrm{Prc}_{jk})(\rho_r)(E_r)(T_r)}{(X_{jk})(\rho_x)(E_{jk})} \tag{2}$$

where Prc_{jk} is the volume of precipitation with density ρ_r and chemical potential energy E_r; T_r is the transformity of the precipitation and X_{jk} is the volume of runoff with density ρ_x and chemical potential energy E_{jk}.

The module presents values calculated by Odum et al. (2000) for the density (1.0 g/cm^3), water chemical potential energy (4.94 J/g) and transformity of the precipitation (30,500 sej/J). Nevertheless, it is possible to change the value of the chemical potential energy by varying the concentration of TDS for precipitation.

In terms of the geopotential energy Egp_{jk}, as the second component of the emergy value, it can be estimated as usual with an external process from this module through equation (3) (Odum, 1996; Brown et al., 2010), where g is the gravity aceleration and z_k is the average altitude of the study unit k.

$$\mathrm{Egp}_{jk} = (X_{jk})(\rho_x)(g)(z_k) \tag{3}$$

3.2. *Module to calculate the filling index*

The modeling of groundwater depth and the calculation of the filling index (Phases 4 and 5 in Fig. 2) are processes performed by the module represented in Fig. 4. To this end, the point location of the piezometric network and the corresponding database of an aquifer are used to interpolate the groundwater level for each year recorded. Thus, it is possible to calculate the value of the filling index (FI) in a spatially distributed manner using Equation (4) (Pernía et al., 2005; Vrba and Lipponen, 2007; Van Camp et al., 2010):

$$\mathrm{FI} = \frac{\mathrm{PL}_{\max} - \mathrm{PL}_i}{\mathrm{PL}_{\max} - \mathrm{PL}_{\min}} \tag{4}$$

where PL_i is the depth (m) of the piezometric level at time i, and $\mathrm{PL}_{\min}$ and $\mathrm{PL}_{\max}$ are the minimum and maximum depths, respectively, of the piezometric levels during the period with records (Fig. 5).

In this case, since the process is dynamic, the calculation of the FI reflects the status of the aquifer with respect to previous years. Thus, the FI can be used to: (a) identify the intensive exploitation zones (when FI = 0) and (b) calculate water recharge volumes by multiplying the effective porosity of the aquifer by the volume of soil corresponding to the difference between current and minimum recorded groundwater levels. Some additional results can also be obtained, such as the behavior of the depth and the mean variation of groundwater levels (positive variations indicate depletion and negative variations reflect recharge).

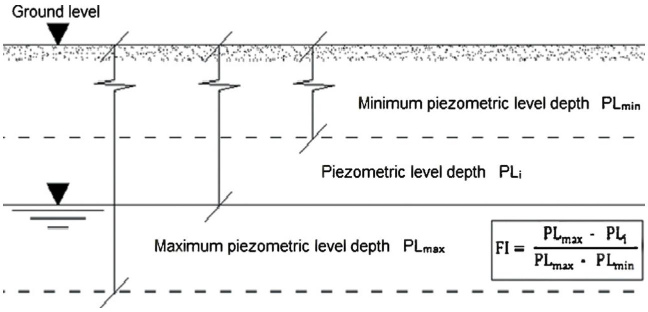


Fig. 5. Graphical representation of the filling index.

The emergy value associated with groundwater is estimated in an analogous manner to surface water. Equation (1) is used for calculating of water chemical potential energy with C_{2jk} as the TDS amount in the groundwater. Transformity of groundwater is estimated through equation (2) taking into account x_{jk} as the ratio of infiltration. Finally, the altitude of groundwater in the geopotential energy (equation (3)) can be considered as the altitude of ground surface minus the piezometric level depth of groundwater table.

4. Study zone

The modules developed to calculate the inter-annual variation in emergy and volumes of renewable groundwater resources were applied to the basins of the Upper Course of the Lerma River (UCLR) and the Santa Catarina River (SCR). These zones, which are separated by the Tropic of Cancer, are part of the Lerma-Santiago-Pacific and the Bravo River regions, which are two of the regions with the greatest contributions to Mexico's gross national product, 14.29% each (CONAGUA, 2011). Fig. 6 shows the location of the UCLR basin, which encompasses the Toluca metropolitan area with roughly 1.6 million inhabitants. The SCR basin includes a large portion of the metropolitan area of Monterrey (40.56%, INEGI, 2001), with roughly 4 million inhabitants (INEGI, 2010). The present work includes the watersheds in the SCR basin as a function of land elevations only, due to a lack of information about drainage in the urban zone, and given that the natural flow is respected as it crosses the urban zone.

The UCLR basin has an average altitude of 2600 m.a.s.l. The valley has a sub-humid temperate climate and a mean annual rainfall depth of 900 mm, while the mountainous region has a semi-cold and cold climate with a mean annual rainfall depth of 1200 mm (Esteller and Díaz-Delgado, 2002). The Valley of Toluca aquifer (VTA) functions freely, reaching depths of over 500 m in the valley (Esteller et al., 2011). According to official data (DOF, 2009) the VTA (with a recharge of 336.8E + 06 m^3/year, discharge of 53.6E + 06 m^3/year and extracted volume of 422.4E + 06 m^3/year) has a deficit of 152.4E + 06 m^3/year, which is obtained from the groundwater reserves. The overexploitation of the VTA – reflected by a continual depletion between 0.1 and 1.6 m/year (Fonseca et al., 2013) – is the reason for spatially identifying the water resources extracted from the groundwater reserves and classifying them as non-renewable for management processes that foster the conservation of this water body.

The SCR basin is located at an average altitude of 1460 m.a.s.l. The valley has a semi-warm dry climate and a mean annual rainfall depth of 400 mm; the high regions have a semi-warm sub-humid climate with a mean annual rainfall depth of 800 mm (Guerra-Cobián, 2007; INEGI, 2012). The aquifer of the Monterrey metropolitan area (AMMA) has a recharge of 68.2E + 06 m^3/year,

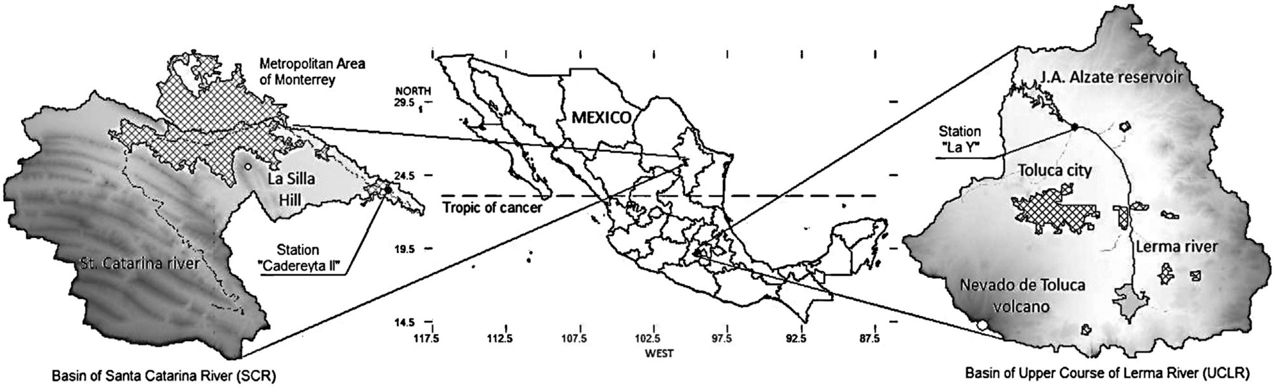


Fig. 6. Basins of the Upper Course of the Lerma River (UCLR) and Santa Catarina River (SCR).

a discharge of 24.5E + 06 m^3/year and an extracted volume of 37.7E + 06 m^3/year. As a result of the total volume of water provided (106.3E + 06 m^3/year), it has a water balance deficit of 62.6E + 06 hm^3/year (DOF, 2011). It is worth mentioning that in the case of the AMMA, 13.7E + 06 m^3/year in infiltration comes from precipitation complemented by lateral recharges and leaks in the urban systems of water supply and sewage. Similar to the VTA, this aquifer functions freely and reaches a depth of approximately 53 m and 100 m on occasion (CONAGUA, 2002). Because of the low rainfall depth value and the difference between the flow provided and that extracted from the aquifer, the emergy accounting of surface water and groundwater can provide information for the integrated management of water resources in order to more efficiently use water resources in terms of energy.

With a simple comparison of the volumes of precipitation between the UCLR and SCR basins, it would seem logical that the supply of water in the UCLR basin would come from surface water while the SCR would have to look for alternative sources. Nevertheless, the proportion of the supply sources used appears to be reversed. For the UCLR basin, 95.8% (474E + 06 m^3/year) of the water comes from the VTA and the rest from imported surface water (Fonseca et al., 2012; IMTA, 2009); while for the SCR basin, 91.0% (363E + 06 m^3/year) of the water comes from imported surface water and is complemented by alternative sources, including water from the AMMA (SAyDM, 2011; DOF, 2011). This is because the surface water in the UCLR basin is not suitable for human consumption, or industrial use, due to intense contamination caused by industrial development and demographic growth. And in the SCR basin, the AMMA aquifer can present a strong sensitivity to precipitation events, and on the other hand, where the deep aquifers can reach depths up to 2000 m (SAyDM, 2011).

With respect to water quality, total dissolved solids (TDS) reflect a disparity between the supply sources in both study zones. The quality of the surface waters in the UCLR basin vary throughout the main river from 300 to 500 mg/L of TDS during the rainy season and 940 to 1525 mg/L during the dry season (Fall et al., 2007). Although located in zones with high exploitation, the groundwater in the VTA show lower concentrations, with values up to 194 mg/L (Martín del Campo, 2010). In the case of the SCR, the TDS values for surface water are roughly 285 mg/L while in the AMMA they vary between 431 and 579 mg/L (INEGI, 2001).

Finally, to use the modules developed in Idrisi, it was necessary to perform a water balance for both basins and a distributed calculation of the runoff and infiltration rates. The information needed for this was taken from images of monthly mean temperature, altitude, ground cover and type of soil, obtained from WorldClim (2006) and INEGI (2012). To calculate the spatial distribution of precipitation, information was used from 79 weather stations in the UCLR basin and 31 in the SCR basin (SMN, 2006). To calculate base flows, records of daily rates were used (CONABIO, 2002) from the "La Y" and "Cadereyta II" hydrometric stations located at roughly 13 and 10 km upstream from the basin outlet of the UCLR and SCR, respectively. The area that drains into the "La Y" hydrometric station represents 74% of the UCLR basin (208592 ha) while the area draining toward the "Cadereyta II" represents 99% of the SCR basin (183986 ha).

5. Results

Emergy value of water resources was monthly estimated for sub-basins of the UCLR and SCR. The delimitation of the sub-basins was conducted to identify the zones with greater emergy value. Emergy tables (Tables 2 and 3) were built as examples of the emergy accounting for both the UCLR and the SCR basins respectively in the month of September. Notes of tables are shown in Appendix A.

Although emergy value of geopotential energy is estimated, the evaluation of water resources and development of strategies was carried out taking into account just the emergy value associated with the water chemical potential energy. This because, on one hand joint water resources management with urban and agriculture uses, requires strategies where emergy value is varying according to the volume of water and its quality. And, on the other hand, geopotential energy is directly proportional just to the ratio of runoff and infiltration, that means, if runoff or infiltration increases its ratio 1 m^3/month, its emergy value increases 4.94E + 08 sej/month -since 1 m^3/month × 1000 kg/m^3 × 9.81 m/s^2 × 5.04E + 04 sej/J (Odum, 2000; Brown et al., 2010) = 4.94E + 08 sej/month and altitude z remains constant-. This reason allows us hereafter make mention of emergy value in terms just of water chemical potential energy.

5.1. Surface water streams

Fig. 7 shows monthly mean runoff volumes and variability for the UCLR and SCR basins. The annual mean runoff was calculated at 125.95 and 1.35E + 06 m^3/year respectively. For the spatial variation of monthly mean runoff for the SCR sub-basins, a standard deviation of 0.6E + 06 m^3 was observed for the month of September, with no significant runoff during the remaining months. In the UCLR sub-basins, in addition to spatial variations (with standard deviations of 3.9E + 06, 12.1E + 06, 11.0E + 06 and 7E + 06 m^3 for June through September, respectively), a monthly mean runoff of

Table 2
Emergy value, UEV and transformity of water resources in the UCLR basin (September).

	Item	Input	Unit per month	Reference (UEV)	UEV (sej/unit)	Emergy (sej/month)
	Surface water of Sub-basin 10					
1	Geopotential	1.48E+14	J	2	5.04E+04	7.43E+18
2	Chemical potential	2.51E+13	J	1	6.93E+05	1.74E+19
	Surface water of Sub-basin 21					
3	Geopotential	3.39E+13	J	2	5.04E+04	1.71E+18
4	Chemical potential	5.92E+12	J	1	1.18E+06	7.00E+18
	Surface water of Sub-basin 22					
5	Geopotential	3.71E+13	J	2	5.04E+04	1.87E+18
6	Chemical potential	6.27E+12	J	1	6.56E+05	4.11E+18
	Surface water of Sub-basin 31					
7	Geopotential	1.49E+14	J	2	5.04E+04	7.53E+18
8	Chemical potential	2.60E+13	J	1	4.32E+05	1.12E+19
	Surface water of Sub-basin 32					
9	Geopotential	1.20E+13	J	2	5.04E+04	6.07E+17
10	Chemical potential	2.30E+12	J	1	1.61E+06	3.71E+18
	Surface water of Sub-basin 41					
11	Geopotential	1.01E+14	J	2	5.04E+04	5.09E+18
12	Chemical potential	1.69E+13	J	1	4.75E+05	8.04E+18
	Surface water of Sub-basin 42					
13	Geopotential	4.76E+13	J	2	5.04E+04	2.40E+18
14	Chemical potential	8.48E+12	J	1	6.78E+05	5.75E+18
	Surface water of Sub-basin 51					
15	Geopotential	1.23E+13	J	2	5.04E+04	6.19E+17
16	Chemical potential	2.32E+12	J	1	4.40E+05	1.02E+18
	Surface water of Sub-basin 52					
17	Geopotential	8.68E+13	J	2	5.04E+04	4.37E+18
18	Chemical potential	1.45E+13	J	1	6.91E+05	1.00E+19
	Surface water of Sub-basin 61					
19	Geopotential	6.19E+13	J	2	5.04E+04	3.12E+18
20	Chemical potential	1.08E+13	J	1	5.21E+05	5.64E+18
	Surface water of Sub-basin 62					
21	Geopotential	3.01E+13	J	2	5.04E+04	1.52E+18
22	Chemical potential	5.67E+12	J	1	6.12E+05	3.47E+18
	Groundwater of VTA					
23	Geopotential	2.17E+15	J	2	5.04E+04	1.09E+20
24	Chemical potential	3.91E+14	J	1	2.50E+05	9.76E+19
	Total emergy	1.05E+14	g		3.05E+06	3.21E+20

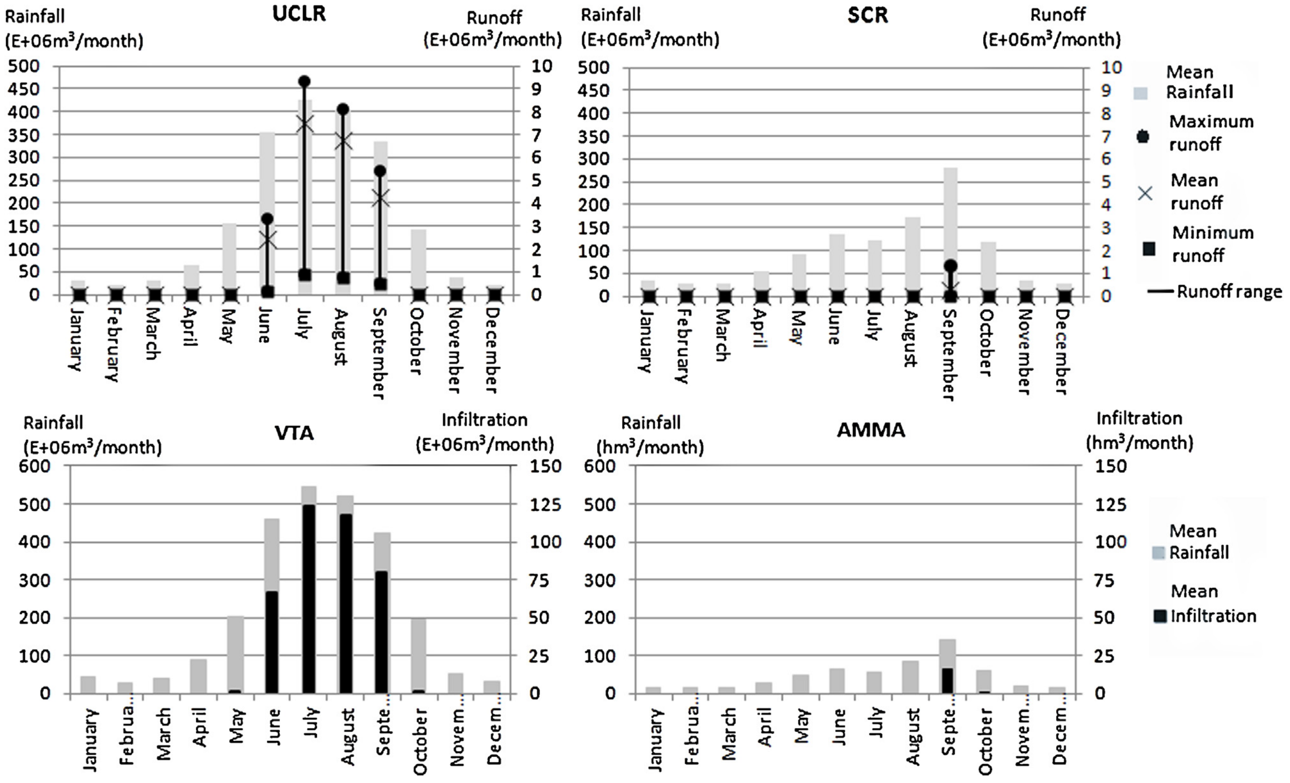


Fig. 7. Monthly runoff for the basins of UCLR and SCR and monthly infiltration for VTA and AMMA. UCLR: Upper Course of Lerma River; SCR: Santa Catarina River; VTA: Valley of Toluca aquifer; AMMA: Aquifer of the Monterrey metropolitan area.

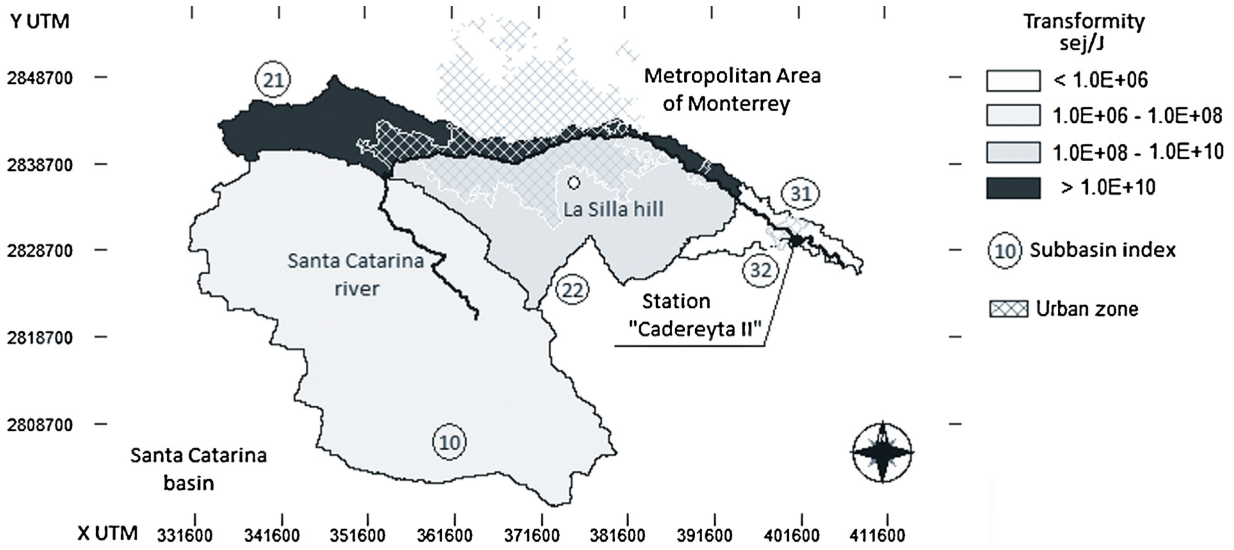


Fig. 8. Weighted mean transformity of surface water resources in the SCR basin. SCR: Santa Catarina river.

31.49E + 06 m^3 (as the sum of each sub-basin runoff) was observed, with a standard deviation of 14E + 06 m^3.

In the sub-basins of the Santa Catarina River (Fig. 8), 3 of the 5 sub-basins contributed an emergy flow, with an observed weighted mean for runoff volumes of 4.58E + 13 sej/m^3 and a standard deviation of 3.21E + 16 sej/m^3. The weighted mean of transformity obtained was 9.36E + 05 sej/J with a standard deviation of 6.54E + 09 sej/J. The sub-basin indexed with the number 10 was the one that contributed the most runoff volume and the least transformity (5.92E + 06 sej/J), while the basin indexed with the number 21 reflected the highest transformity values (1.13E + 10 sej/J). In terms of the base flow contribution, the registries included were those corresponding to rates greater than zero for the Cadereyta II station. The mean value for the base flow was calculated to be 0.25 m^3/s, including the portion of the basin downstream from the station. Because the contribution of groundwater by the intermittent base flow is dependent on precipitation, by definition 100% of the surface water resources can be considered renewable.

In the case of the UCLR basin (Fig. 9), a weighted mean UEV of 2.79E + 12 sej/m^3 was calculated for runoff volume, with a standard deviation of 7.17E + 12 sej/m^3 and a weighted mean transformity of 5.75E + 05 sej/J was calculated with a standard deviation of 1.4E + 06 sej/J. With respect to the sub-basins (Fig. 10), the highest transformity values were presented in those located to the left of the Lerma River, where the largest proportion of the urban zone is found. The sub-basin indexed with the number 32 shows a transformity 2.9 times greater than the sub-basin with the least transformity (Index 51), reflecting the largest concentration of contaminants discharged into the surface water bodies. This sub-basin is where most of the industries in the region are located and, although they have wastewater treatment plants, the greatest temporal variation is found here, as shown in Fig. 10 (transformity in June was roughly 10 times greater than in July, while the other sub-basins differed by a factor of only 3 times their minimum values).

The daily flow records in the UCLR show a base flow not greater than 1 m^3/s up until 1995, and variations from 2.5 to 7 m^3/s between 1995 and 2006. The base flow rate was calculated at 4.9 m^3/s using the volume of water provided per unit area and taking into account the portion of the basin downstream from the “La Y” hydrometric station. In this case, the base flow reflects a deteriorated state (from 1522 to 2558 mg/L of TDS) which is similar to the quality of the wastewater discharged. Therefore, the absence of a significant contribution of groundwater is presumed, and thus all the surface water resources are considered to be renewable.

5.2. Groundwater

The infiltration rates, due to precipitation, calculated for the VTA and the AMMA were 388.13E + 06 m^3/year and 16.01 hm^3/year, respectively. The weighted mean of UEV for the VTA was 1.39E + 12 sej/m^3 and the transformity was 2.83E + 05 sej/J; for the

Table 3
Emergy value, UEV and transformity of water resources in the SCR basin (September).

	Item	Input	Unit per month	Reference (UEV)	UEV (sej/unit)	Emergy (sej/month)
	Surface water of Sub-basin 10					
1	Geopotential	2.54E + 13	J	2	3.72E + 04	9.43E + 17
2	Chemical potential	6.57E + 12	J	1	5.92E + 06	3.89E + 19
	Surface water of Sub-basin 21					
3	Geopotential	1.04E + 09	J	2	3.72E + 04	3.88E + 13
4	Chemical potential	6.20E + 08	J	1	1.13E + 10	7.02E + 18
	Surface water of Sub-basin 22					
5	Geopotential	5.33E + 10	J	2	3.72E + 04	1.98E + 15
6	Chemical potential	3.81E + 10	J	1	4.12E + 08	1.57E + 19
	Groundwater of AMMA					
7	Geopotential	9.90E + 13	J	2	3.72E + 04	3.68E + 18
8	Chemical potential	7.80E + 13	J	1	4.12E + 05	3.21E + 19
	Total emergy	1.73E + 13	g		5.67E + 06	9.83E + 19

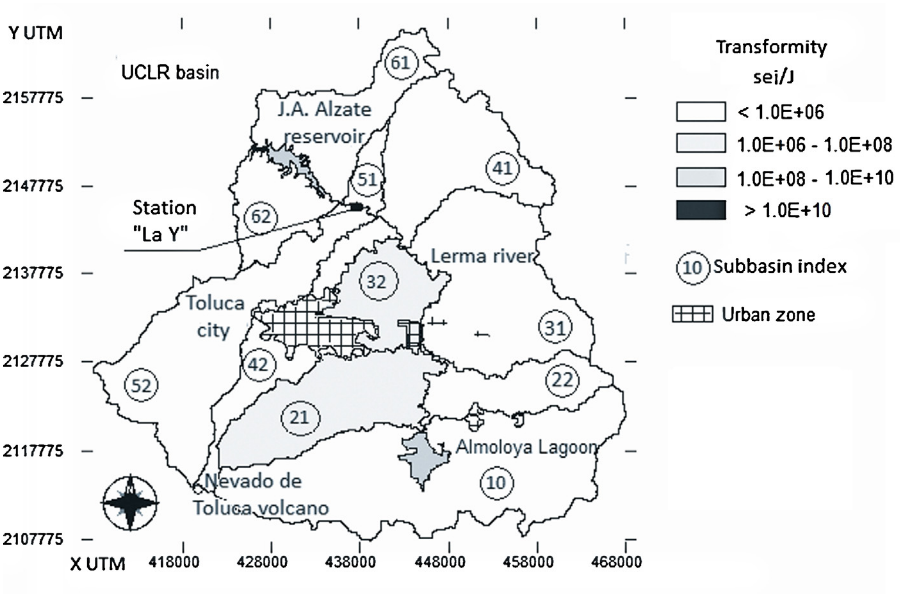


Fig. 9. Weighted mean transformity of surface water resources in the UCLR basin. UCLR: Upper Course of Lerma River.

AMMA, the weighted mean of UEV was 3.15E + 13 sej/m^3 and the transformity was 6.47E + 06 sej/J.

The information obtained from the piezometric records (Fig. 11) indicates that the mean groundwater level has decreased in both aquifers, in spite of sporadic recoveries. Nevertheless, the decrease in groundwater was not homogeneous (the maximum depth reached by the piezometric level was 92.9 m in the VTA compared to 63.1 m in the AMMA). In other words, recharge zones exist where volumes of water resources can be considered renewable.

The mean filling index calculated for the VTA (Fig. 12) was 0.11 during 2009, where most of the area maintained a value of zero. The volume of water resources that can be considered renewable is as high as 156.48E + 06 m^3/year, of which only 97.31E + 06 m^3/year can be exploited due to its location within the region of the valley. Complementary extracted volumes come from the aquifer reserves and can therefore be considered as a non-renewable resource.

Fig. 12 shows that in the southern portion of the Metropolitan Area of Monterrey (about 78E + 04 m^2 at the west of La Silla hill) the filling index reached a range between 0.5 and 0.9 during the year 2012. Most of the area had a filling index between 0 and 0.20 and in some zones it reached 0.40, making it possible to obtain a volume of renewable water resources of 47.61E + 06 m^3/year (taking into account infiltration through lateral recharge and leaks in urban networks).

Table 4 was created with these results, which shows the calculation of volumes of water resources used in the UCLR and SCR basins according to their classification as renewable and non-renewable. The percentage of renewable resources used in the UCLR and SCR basins was less than half (19.7 and 11.4%, respectively). In this table, all the surface water resources in the SCR are considered to be used since that volume reaches a dam that supplies water to the city downstream from the basin.

6. Discussion

The calculation of weighted mean of UEV and transformity (Table 5) makes it possible to conduct an emergy accounting similar to the traditional procedure of using annual values of precipitation, runoff and infiltration. Thus, between the two basins and aquifers it is possible to deduce that: (a) the water resources with the greater

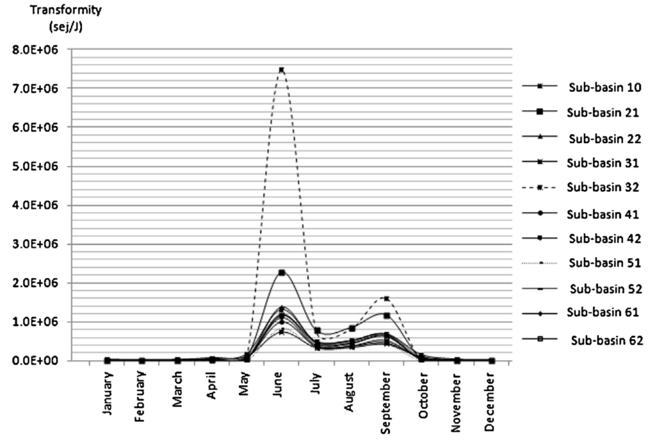


Fig. 10. Temporal trend of the transformity in the UCLR subbasins. UCLR: Upper Course of Lerma River.

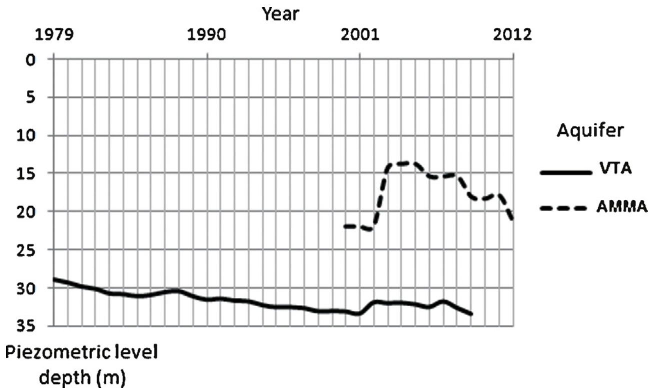


Fig. 11. Temporal trend of the groundwater level in VTA and AMMA. VTA: Valley of Toluca aquifer; AMMA: Aquifer of the Monterrey metropolitan area.

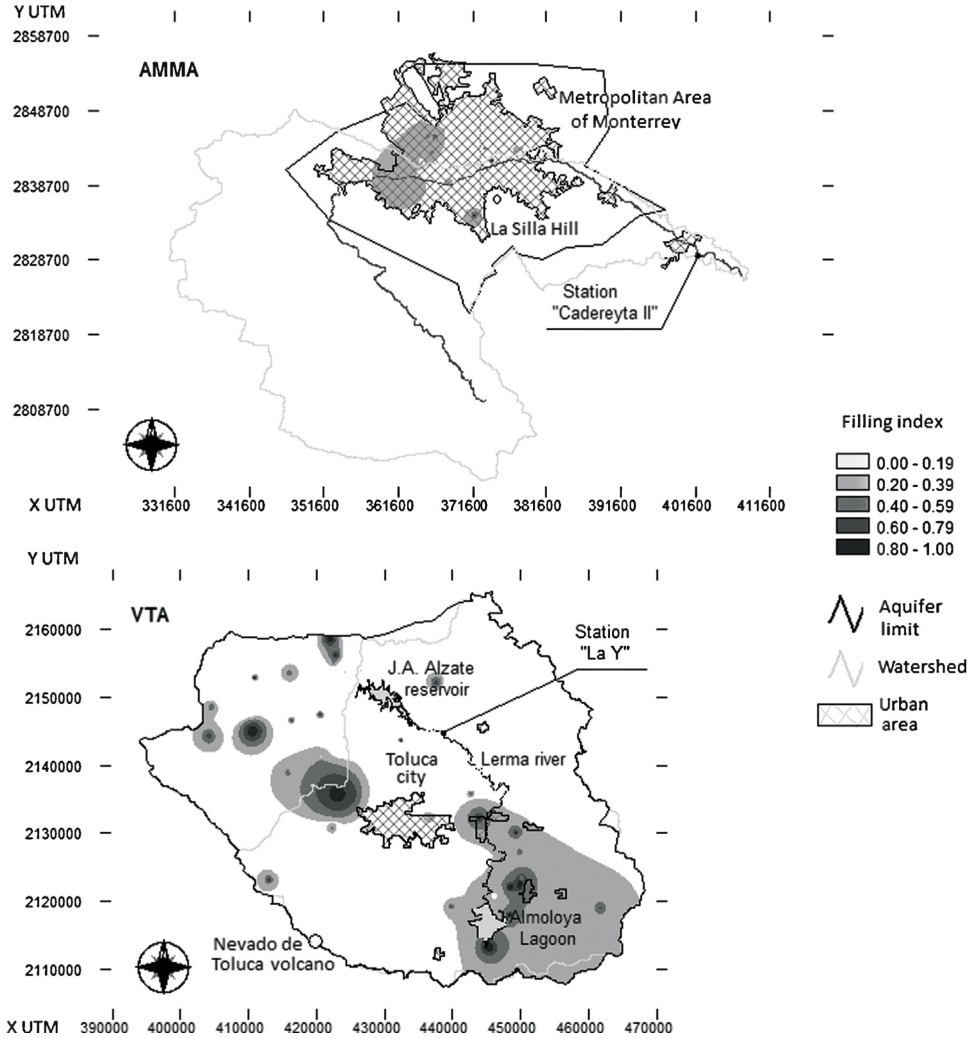


Fig. 12. Filling index in VTA and AMMA. VTA: Valley of Toluca aquifer; AMMA: Aquifer of the Monterrey metropolitan area.

potential for use are those corresponding to the VTA (higher annual emergy flow and lower transformity); (b) the water resources with the lowest potential for use correspond to the surface streams in the SCR basin (lower annual emergy flow and higher transformity) and (c) the surface water resources of the UCLR continue to have the poorest water quality, as reflected in the lowest water chemical potential energy.

Table 4
Renewable and non-renewable water resources in the basins of UCLR and SCR.

		UCLR	SCR
[1]	Total demand (2010)	495	400
	Surface water		
[2]	Disponibility	155.34	7.96
[3]	Renewable	0	7.96
[4]	Non-renewable	0	0
	Groundwater		
[5]	Disponibility	97.31	47.61
[6]	Renewable	97.31	37.7
[7]	Non-renewable	376.69	0
[8]	Import water	21	354.34
([3] + [6])/[1]	Percentage of renewable resource used	19.7%	11.4%

UCLR: Upper Course of the Lerma River; SCR: Santa Catarina River. Units in hm^3/year.

In addition, a similarity in terms of energy can be seen in the use of surface water and groundwater resources within the same region. The quotient between the UEV for surface water in the SCR and groundwater in the AMMA was 1.45, greater than the ratio of 1.44 corresponding to its transformity. In the UCLR basin, quotient between the UEV for surface water and groundwater was 1.99, less than the 2.03 corresponding to its transformity. These values have two meanings. First, the difference between infiltration and runoff events is less significant in the SCR basin than in the UCLR ($1.45 < 1.99$). And second, the presence of contaminants in the surface water of the UCLR has an impact in the sense that the water chemical potential energy has a greater influence on emergy than hydrological events (otherwise, the emergy per volume ratio would be less or equal to the transformity ratio).

This emergy accounting can justify the use of groundwater in both regions. Nevertheless, it does not define a threshold at which the extracted water volume affects the aquifer reserves, nor does it identify, when applicable, the location and time for the use of water that is less suitable in terms of energy.

Therefore, the emergy accounting based on temporal and spatial variations, as well as the establishment of a criterion to classify water as a renewable or non-renewable resource make it possible to create strategies for the integrated use of water resources

Table 5
Emergy and transformity of water resources in the basins of UCLR and SCR.

	Element	Energy Flow (J/year)	Transformity (sej/J)	Annual Emergy (sej)	Emergy per mass (sej/g)	Emergy per volume (sej/m^3)
1	Surface water (UCLR)	6.13E + 14	5.75E + 05	3.52E + 20	2.79E + 06	2.79E + 12
2	Groundwater (VTA)	1.91E + 15	2.83E + 05	5.40E + 20	1.39E + 08	1.39E + 12
3	Surface water (SCR)	6.62E + 12	9.33E + 06	6.20E + 19	4.58E + 07	4.58E + 13
4	Groundwater (AMMA)	7.80E + 13	6.47 + E06	5.05E20	3.15E + 07	3.15E + 13

Notes: 1. The energy flow was estimated as the product of runoff rates (for the subbasins of UCLR and SCR) and infiltration (for AVT and AAMM) with the weighted average of the chemical potential with respect to runoff and infiltration rates month (4.86, 4.92, 4.90 and 4.87 J/g respectively). 2. Emergy per unit was estimated as a weighted average with respect to rates of runoff and infiltration basins and aquifers respectively. 3.Annual emergy is the product of emergy per unit and the energy annual flow. 4. The emergy by volumes was estimated as the weighted average with respect to the rates of runoff in the infiltration of the sub-basins and the aquifers respectively. 5.The emergy per mass is the quotient of the emergy per volume and the density of the water (E + 06 g/m^3).

in the region. These strategies are composed of: (a) the calculation of volumes of water resources with the potential for use, (b) the location of supply sources to establish monthly variability in the volumes of water provided and (c) proposed fee schedules according to the emergy requirements of the supply source used, and even restrictions on urban growth.

With respect to the first two strategies and based on Table 4, an obvious exploitation of non-renewable resources (76% of total resources) can be seen in the UCLR basin, as well as a preference for satisfying water needs with imported resources rather than surface resources. Through the inter-annual variation in emergy and transformity of surface water in the UCLR basin, shown in Fig. 10, the lowest UEV (approximately 2.1E + 12 sej/m^3) can be identified during the months of July and August. In addition, in 5 of 13 of the sub-basins (indexed with numbers 31, 41, 51, 61 and 62) the lowest transformity values (between 4.25E + 05 and 5.34E + 05 sej/J) were observed for surface waters. Thus, an annual volume of water up to 41E + 06 m^3 from these sub-basins can be considered to have the potential for use since its transformity is 1.5 to 1.9 times greater than that of groundwater, equal to 2.83E + 05 sej/J. The emergy for using this volume is 7.32E + 19 sej/year, while the same volume of groundwater has an emergy of 4.18E + 19 sej/year. Although this reflects an increase of 3.14E + 19 sej/year in the emergy of the system (23% of the total emergy due to chemical potential energy), the percentage of renewable resources also increases by 28%.

In Table 4 for the SCR basin, it can be seen that a scarcity of water resources has required demand to be satisfied with imported water, although it is still possible to mitigate those needs with groundwater by roughly 2.5% of total demand during dry months (November to March). The volume corresponding to this proportion is 1.82E + 06 m^3/month extracted in the northwest and southern portions of the Monterrey metropolitan area, according to the filling index (FI) shown in Fig. 12. It is thereby possible to obtain a decrease of as much as 1.29E + 18 sej/year (representing 9% of the total emergy due to water chemical potential energy) as a result of the difference in UEV between surface water and groundwater [(4.57E + 13 −3.15E + 13) sej/m^3 × 9.1E + 06 m^3/year = 1.29E + 18 sej/year].

The substitution of supply sources is more complicated than the sole comparison of UEV and transformity of water resources. For example: (a) the exploitation of groundwater can result in high emergy flows due to the large amount of energy needed to raise the water from the phreatic level to the surface and (b) the emergy flow related to the treatment of surface water can increase as the degree of contamination increases. It is therefore necessary to perform an emergy accounting that includes the energy consumption corresponding to the processes of extraction, conduction, treatment and distribution of water associated with each source. Nevertheless, the calculation of emergy and the classification of water resources according to their renewability serve as a guide for compensating the energy consumptions mentioned above with the conservation of water bodies, in consideration of their sustainability. The energy consumption associated with supply processes is provided by the socioeconomic system through a fee schedule. In addition, it is possible to establish urban growth patterns according to the spatial distribution of water resources that are more suitable in terms of emergy. However, these activities, which compose the third strategy, are not part of this study but open the way for future projects.

7. Conclusions

Emergy accounting allows both determining an added value of water, which provide the arguments for decrease intensive exploitation of water bodies with larger UEV, and identifying the location and time to use the water resources.

The results have been obtained using a scientific basis and a geoinformatics platform to calculate the spatial and temporal variations that affect the UEV and transformity values of water resources in physiographic and geohydrological units such as basins and aquifers. In the case of the UCLR basin, it was possible to calculate a volume for the potential use of surface water from 5 of the 13 sub-basins during the months of July and August. In the SCR basin, an unused volume of renewable groundwater was calculated, which represents a decrease in emergy if used during the dry months.

In addition, a criterion has been identified to determine the intensive exploitation of aquifers and consider those volumes as non-renewable resources within the framework of an integrated water management plan. In this regard, it has been determined that in the UCLR basin, only 20% of the water demand is satisfied with renewable water resources, 4% with imported resources and the majority (76%) with non-renewable water resources. In the SCR basin, the use of its non-renewable resources was not identified, with 89% of the supply demand met by imported resources and 11% by renewable water resources. In both cases, the extreme fragility of the systems can be highlighted, since the sustainability of the water supply must be improved given that in both basins renewable resources account for less than half of the water resources used to satisfy demand.

Finally, the modules developed for the GIS are considered to be an advance and provide motivation to build other modules for future investigations, in order to calculate the emergy flows of resources pertaining to socioeconomic systems (water extraction, conduction and treatment processes, among others), for the purpose of sustainable water resources management systems.

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Appendix A.

Notes for Table 2.

1 Input: runoff = 5.17E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2907 m; surface energy = (Eq. (3)) = 1.48E + 14 J/month

2 Surface water: runoff = 5.17E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,280 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy = (Eq. (1)); energy in surface water = 5.17E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.85 J/g = 2.51E + 13 J/month; rain = 75.47E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

3 Input: runoff = 1.24E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2795 m; surface energy = (Eq. (3)) = 3.39E + 13 J/month

4 Surface water: runoff = 1.24E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 998,870 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 1.24E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.79 J/g = 5.92E + 12 J/month; rain = 30.40E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

5 Input: runoff = 1.39E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2904 m; surface energy = (Eq. (3)) = 3.71E + 13 J/month

6 Surface water: runoff = 1.39E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,033 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 1.39E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.81 J/g = 6.27E + 12 J/month; rain = 17.85E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

7 Input: runoff = 5.38E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2831 m; surface energy = (Eq. (3)) = 1.49E + 14 J/month

8 Surface water: runoff = 5.38E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,128 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 5.38E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.83 J/g = 2.60E + 13 J/month; rain = 48.76E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

9 Input: runoff = 4.75E + 05 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2587 m; surface energy = (Eq. (3)) = 1.20E + 13 J/month

10 Surface water: runoff = 4.75E + 05 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,313 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 4.75E + 05 m^3/month × 1.0E + 06 g/m^3 × 4.85 J/g = 2.30E + 12 J/month; rain = 16.13E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

11 Input: runoff = 3.56E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2973 m; surface energy = (Eq. (3)) = 1.01E + 14 J/month

12 Surface water: runoff = 3.56E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,576 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 3.56E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.89 J/g = 1.69E + 13 J/month; rain = 34.92E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

13 Input: runoff = 1.74E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2795 m; surface energy = (Eq. (3)) = 4.76E + 13 J/month

14 Surface water: runoff = 1.74E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,529 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 1.74E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.88 J/g = 8.48E + 12 J/month; rain = 24.96E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

15 Input: runoff = 4.77E + 05 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2628 m; surface energy = (Eq. (3)) = 1.23E + 13 J/month

16 Surface water: runoff = 4.77E + 05 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,430 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 4.77E + 05 m^3/month × 1.0E + 06 g/m^3 × 4.87 J/g = 2.32E + 12 J/month; rain = 4.44E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

17 Input: runoff = 2.98E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2965 m; surface energy = (Eq. (3)) = 8.68E + 13 J/month

18 Surface water: runoff = 2.98E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,431 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 2.98E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.87 J/g = 1.45E + 13 J/month; rain = 43.60E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

19 Input: runoff = 2.25E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2807 m; surface energy = (Eq. (3)) = 6.19E + 13 J/month

20 Surface water: runoff = 2.25E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,069 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 2.25E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.82 J/g = 1.08E + 13 J/month; rain = 24.51E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

21 Input: runoff = 1.18E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2602 m; surface energy = (Eq. (3)) = 3.01E + 13 J/month

22 Surface water: runoff = 1.18E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,011 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 1.18E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.81 J/g = 5.67E + 12 J/month; rain = 15.08E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

23 Input: infiltration = 79.48E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 2782 m; surface energy = (Eq. (3)) = 2.17E + 15 J/month

24 Groundwater: infiltration = 79.48E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,806 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in groundwater = 79.48E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.92 J/g = 3.91E + 14 J/month; rain = 423.84E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

Notes for Table 3.

1 Input: runoff = 1.34E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 1933 m; surface energy = (Eq. (3)) = 2.54E + 13 J/month

2 Surface water: runoff = 1.34E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,715 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 1.34E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.91 J/g = 6.57E + 12 J/month; rain = 168.72E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

3 Input: runoff = 1.26E + 02 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 844 m; surface energy = (Eq. (3)) = 1.04E + 09 J/month

4 Surface water: runoff = 1.26E + 02 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 998,715 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 1.26E + 02 m^3/month × 1.0E + 06 g/m^3 × 4.91 J/g = 6.20E + 08 J/month; rain = 30.48E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

5	Input: runoff = 7.76E + 03 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 701 m; surface energy = (Eq. (3)) = 5.33E + 10 J/month
6	Surface water: runoff = 7.76E + 03 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,715 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in surface water = 7.76E + 03 m^3/month × 1.0E + 06 g/m^3 × 4.91 J/g = 3.81E + 10 J/month; rain = 68.15E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).
7	Input: infiltration = 15.98E + 06 m^3/month; gravity = 9.81 m/s^2; density = 1E + 10 kg/m^3; elevation = 631 m; surface energy = (Eq. (3)) = 9.90E + 13 J/month
8	Groundwater: infiltration = 15.98E + 06 m^3/month; density = 1.0E + 06 g/m^3; water concentration = 999,500 mg/L; sea water concentration = 965,000 mg/L; R = 8.33 J/mol K, T = 300 K, w = 18 g/mol, Gibbs free energy (Eq. (1)); energy in groundwater = 15.98E + 06 m^3/month × 1.0E + 06 g/m^3 × 4.88 J/g = 7.80E + 13 J/month; rain = 139.41E + 06 m^3/month; rain density = 1.00E + 06 g/m^3; rain transformity = 4.66E + 04 sej/J (Odum, 2000); rain chemical potential energy = 4.94 J/g (Odum, 1996); UEV (Eq. (2)).

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