This is a pre-print of an article published in *Environmental Earth Sciences.* The final authenticated version is available online at: https://doi.org/10.1007/s12665-017-6766-7

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Morphometric and hypsometric analysis in the Tierra Nueva Basin, San Luis Potosí, México

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Received: date / Accepted: date

Abstract In areas with long periods of drought it is essential to implement strategies to manage the available water resource. Tierra Nueva Basin is affected by this situation, consequently the farm production and livestock holdings are affected and the people don't have access to enough water. In this Paper we propose an integrative methodology based on mathematical tools such as hypsometric and morphometric analysis applying geographic information systems. The proposal is strengthened with the aggregation of geological-structural, morphometrical, hypsometrical parameters and climatological information through a precipitation analysis provided by the National Water Commission from 1962 to 2010. According to the available data and the results obtained through the implemented proposal an acceptable level of reliability is inferred allowing to determine areas structurally suitable for the use of surface water and its uptake.
The methodology that we propose facilitates and simplifies the processes of searching and exploring locations suitable for surface water capture in arid and semi-arid zones, identifying in a qualitative and quantitative manner the optimal zone. For the case study, test-and-validation of the methodology the Tierra Nueva basin in San Luis Potosí, México was selected. Tierra Nueva is a semi-arid site where "La Muñeca" dam is located. The results obtained in this work confirm the location of the "La Muñeca" dam as one of the most suitable areas for water collection. The methodology that we propose is a useful tool for the studies of water capturing purposes in arid and semi-arid zones.

Keywords Morphometry · Hypsometry · Tierra Nueva Basin · Water Resource · GIS ·

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1 Introduction

México possesses zones with severe water shortages in contrast to areas with recurrent floods. This requires a quantitative and qualitative analysis of the factors involved in both situations. Such analysis should be focused on providing reliable water resources to be managed and used properly for the benefit of the society.
Quantification and interpretation of topographic changes in a watershed is difficult due to the complex nature of hydrological processes and landform acting on watershed systems sharma2013. Geomorphology is a discipline concerned with quantitative analysis of the surface of the ground pike.Therefore, it can be applied to study a watershed geomorphology as an essential tool to measure and represent the shape of the basin and its evolution Sivakumar.
To perform a geomorphological study implies quantitative information about the terrestrial surface, which can be obtained through morphometrical and hypsometrical techniques.
The morphometric analysis is the mathematical measurement and analysis of the configuration on the sur-

face of the Earth agarwal,clarke1966,vittala. In recent years the morphometric analysis is performed within the GIS systems because of its speed and precision grohmann. The basins shapes match up their drainage, clime and structures magesh2013.
Hypsometry is defined as the analysis of the measurement between the surface elevation and sea level, which provides data to quantitatively study the structural forms in a basin luo,acaraz2011; the hypsometric analysis is primarily used to determine the state of erosion of the watershed and determine its geomorphological state, ie, stability, maturity or inequilibrium (young) sharma2013. An analysis within the basin was made using information from the slopes, adjacent pixels were studied to determine the most likely areas of water catchment.
The region studied in this work is known as Tierra Nueva basin and it is located in the central south of San Luis Potosí and in the north central part of Guanajuato México; according to the National Water Commission (CONAGUA) this area has a high incidence in periods of drought, thus the management and proper usage of scarce water resources in this area is vital.

According with INEGI until 2010 $9,024$ people were living in this zone distributed in 104 locations, 28% of households in this place do not have potable water inegi2010. Situations such as these are the ones that make it necessary to implement various catchment works that, although the stored water can not be used for human consumption, can be used for cleaning and irrigation activities.
Within the Tierra Nueva basin is a dam named La Muñeca; there are also some small catchments of water, however, during the study, we were able to determine areas in which their structural features as well as the state of maturity of the basin and sub-basins, are advantages to make a better use of surface water. Additionally, the level of erosion of the watershed was also defined, and, consequently, it can be inferred susceptibility in the area to carry on with the erosion process.
The starting point of this work was a morphometric and hypsometric analysis in which the measurements and mathematical configuration of the basin region, their levels of erosion and general morphology were obtained. All of this was achieved by the correlation between different layers of structural, geological and climatological data; we use this information to determine appropriate zones to implement water capitation works. The layers were developed in the GRASS GIS 6.4 and Quantum GIS (QGIS) 2.6 software, which are geographical information and open source software grass, and as for the analysis and data extraction from the climatological database, R 2.5 rstat was used.

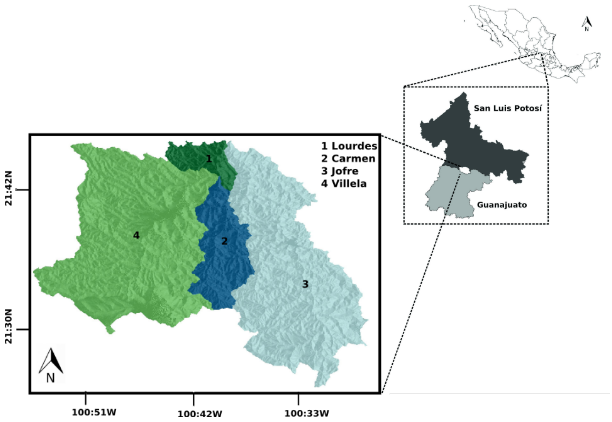

Fig. 1 Generation from CEM 3.0 INEGI2013 and processed in GRASS GIS grass

For this study the continuous Map of Mexican Elevations (CEM 3.0) was used with a resolution of $15m$ per pixel provided by the National Institute of Geography and Statistics INEGI2013, the information was processed in the GRASS GIS 6.4 grass.
The results were validated with climatological, geological and structural information of the study area.

2 Study Area

The Tierra Nueva basin is mainly located in the municipality of Tierra Nueva, another section in Santa María del Río, in the state of San Luis Potosí, and a small part in the municipality of San Luis de la Paz, in Guanajuato state; the studied region has an area of approximately 1,204 km^2 and its elevation is of 1655 to 2616 meters above sea level (MAMSL). The study area is part of the Central Plateau of México, and is bounded by the Sierra Madre Occidental on the west and the Sierra Madre Oriental , on the east, respectively alex$_{t}esis.$
$AccordingtotheEncyclopediaofMunicipalitiesandDelegationsofM$
$Forthisstudy, theTierraNuevabasinwasdividedintofourmajorsubb$
$Jofre, Villela, CarmenandLourdes; Figure1showslocationofTierr$

3 Geological framework

The study area is located within the geological province called Sierra Madre Oriental and the Meseta Central; Figure 2 shows the distribution of rocks in Tierra Nueva basin. The oldest rocks that emerge are the lower and upper Cretaceous corresponding to the formations “El Doctor” and “Soyatal” of the San Luis-Valles platform cossio, including the Holocene. These rocks are divided into two major sequences, sedimentary which are represented by the “Santuario” training calcareous sand

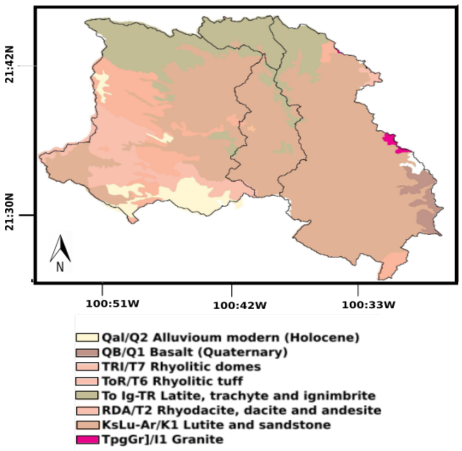

Fig. 2 Tierra Nueva basin litology

composed of fine-grained, thin layering; the Socavón facies of "El Doctor" Formation correspond to the lower Cretaceous composed of clastic limestone, and the "Soyatal" Formation of Upper Cretaceous composed of yellow shales, argillaceous limestone. Cretaceous sedimentary units are covered by volcanic units (rhyolitic ignimbrite) from Cenozoic. A batholith of Tertiary granitic composition margarito is also present.

4 Methodology

For this study the Tierra Nueva basin was divided into four major sub-basins and in them the hypsometric and morphometric analysis was performed independently in order to study it in more detail, as described below.

Morphometric Analysis

The morphometric analysis is used to measure and analyze mathematically the configuration on the surface of the Earth agarwal,vittala. To obtain and evaluate the morphometric parameters, a map of the surface runoff area was generated vijithand, Among the parameters analyzed are:

Stream order S_μ:

According to koshak stream order is considered the most important morphometric characteristic of watersheds; it is used to show the relationship between the segments of the flow, allowing the classification of flows within the basin.
horton points out that a stream segment that has no input from the rest of the currents is classified as a first order stream. He also mentions a segment of the second order is generated from the junction of two segments of the first order while a segment of third order is generated from the union of two second order segments and so on. When there are similar flows in a watershed, it can be said that both flows refer to analogous geological events whose geological ages are almost the same golts,grohmann,horton,strahler1952. For this study an analysis of the basin and sub-basins runoff and their stream order was performed to determine the geological relationship between them.

Runoff density (D_d)

Runoffs density indicates how many of them are found on the surface of the earth, demonstrating how close they are to each other per unit area koshak. High values of D_d are associated with steep slopes; when such values are high, it indicates that rainfall is abundant, and may involve high infiltration in the area. On the other hand, the low density of runoffs indicates much longer flows on the basin chirala. Table 1 shows the classification made by deju the current density can be classified as poor, middle or excellent:

Density	Range (km)
Poor	0.5
Middle	0.5-1.5
Excelent	1.5

Table 1 Deju classification for runoffs density deju

Bifurcation Ratio R_b

Bifurcation ratio can be defined as the relationship between the length of stream of order N_μ with the next length of higher order $N_{\mu+1}$ the bifurcation radius values to the geological and lithological Evolution of Basins, R_b. High values indicate strong runoff pattern, while low values show less structural disturbance strahler1964. The ratio may be obtained by the following equation:

$$R_b = \frac{N_\mu}{N_{\mu+1}} \quad (1)$$

where R_b= Ratio bifurcation
N_μ = Length of stream of given order
$N_{\mu+1}$ =Length of stream of superor order

Length ratio stream Rl

It is the ratio between the average length of a stream of a certain order by the average length of current lower order husain. The change between the current segment can be attributed to variation in the slope and topography, which indicates the stage of development of the currents vittala.

$$RL = \frac{Lu}{Lu-1} \tag{2}$$

Where Lu is the total length of the stream of order 'u' and $Lu-1$ is the total length of the lower order stream.

Frequency of streams Fs

The total number of stream segments of all orders per unit area is known as frequency currenthorton,husain. When you increase the value of Fs then increases the drainage density husain.
To calculate Fs we can apply the following formula das:

$$F_s = \frac{N_u}{A} \tag{3}$$

Where N_u is the total number of streams of all orders is in the basin, and A is the area of the basin on km^2.

Form Factor R_f

Form factor is defined as a dimensionless ratio of watershed area to the square of length of the watershed horton, when the value of form factor is higher (upper tan 0.7854) the watershed has high peak flows for shorter duration aravinda2013.

$$R_f = \frac{A}{L^2} \tag{4}$$

Where R_f is the form factor, L is the total length of the watershed and A is the total area of the watershed.

Basin Elongation Ratio R_e

It is the ratio of diameter of a circle having same perimeter to the maximum length of the basin chirala,schumm. Normally this ratio ranges between $0.4-1.0$, when R_e is low, it will have flow for longer duration aravinda2013.

Circulatory Ratio A_c

The circulatory Ratio is a shape measured linking the basin area with the area of the circle 'A_c' who has the same perimeter as that of basin chirala, when $0.2 \leq A_c \leq 0.8$ indicates mature stage of the basin, low and high values are correlated with youth and old stage aravinda2013.

Hypsometric analysis

The hypsometric analysis relates a section that horizontally crosses the area of the basin with the ground elevation. It is a quantitative method for analyzing the geometry of the catchment area, by describing the load depending on the total area of the basin luo,acaraz2011, with hypsometric analysis is possible to determine the geomorphological evolution of the basin regardless the size gajbhiye, also it can assess their stability, maturity or youth erosive respect to the basin level sharma2013, obtaining hypsometric curves and hypsometric integral gives us important information on the conditions of the basin ritter,sharma2013.The hypsometric curves are obtained by plotting the relative area $\frac{a}{A}$ along the axis, where "a" refers to the relative area of a contour of a contour and "A" is the total area of the basin; and relative elevation $\frac{h}{H}$ along the axis, where "h" is the maximum height of the same level curve and "H" is the maximum height of the basin kusre,luo,sharma2013,strahler1964. Figure 3 shows how the how the values of the hypsometric curve are obtained.
The hypsometric analysis contributes with the values to generate the integrated hypsometric H_i indicates the cycle of erosion strahler1952. This cycle can be divided in three stages: First monadock in this stage the basin is considered old, ans has a value of $H_i < 0.3$. Mature refers to the basin which is in balance and has a value of $0.3 \leq H_i \leq 0.6$. And finally inequilibrium, which is when the basin is in balance the erosion process is slow and has a value of $H_i > 0.6$.
The hypsometric integral provides a measure of the degree of dissection of a landscape evans,acaraz2011, this represents important information when changes within a watershed are studied, because with it is possible to estimate erosion in the area acaraz2011, as is the result of estimating the loss of sediment and surface runoff, which are two hydrological parameters of great importance that occur in these systems sharma2013.
The obtained data indicate the percentage of original rock that still remains in the basins and sub-basins

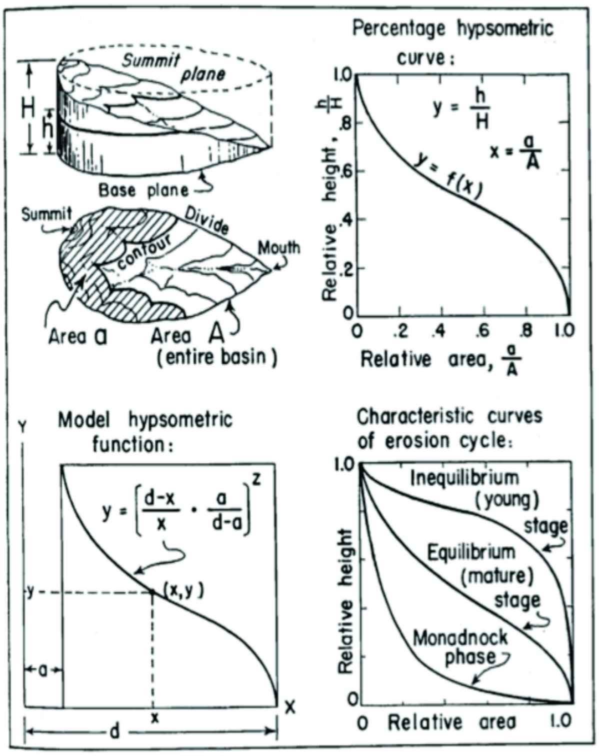

Fig. 3 Ritter hypsometric curve model ritter, as cited by gajbhiye.

gajbhiye. The hypsometric integral values can be obtained with the following formula:

$$HI = \frac{Elev_{mean} - H_{min} H_{max} - H_{min}}{Elev_{max} - Elev_{min}} \quad (5)$$

Precipitation analysis

An important parameter to be analyzed when performing a morphometric study in a basin is precipitation, because this is the main factor of soil erosion; erosion by rainfall varies depending on its intensity nearing2005, considering that inequilibrium basins are more susceptible to erosion, we seek to locate the places where rainfall could structurally affect the implementation of projects for water use. For this study, data from 12 stations available that within, and near the basin of Tierra Nueva were used, such information was provided by the National Meteorological Service (SMN), our analysis was performed with all the information available until 2011, some weather stations have information since 1961 but there are some that only have recent information.
The study consisted of analyzing historical the behavior of the precipitation in the study area and surrounding areas, information is filtered using the convolution operator to determine the existence periods of at least three days of consecutive "heavy" rainfall, considering heavy precipitation as 15 millimeters per day. Figure 6 shows the spatial distribution of this density analysis.

Structural Lineaments

They are defined as linear structural characteristics of tectonic origin that can be localized to be alignments of a long, thin and straight near tone which are visible in satellite imagery guidelines; the guidelines may be faults, fractures, geological formations, power lines, alignment of vegetation or topographic alignment devi2001. By obtaining a satellite image electromagnetic signals collected by the sensors are affected by scattering and absorption of gases and aerosols during the course of the surface of the earth to the sensor song2001, so such images may contain uncalibrated information and/or errors; therefore it is necessary to make corrections before any process. The first procedure was atmospheric correction, consisting of reducing or eliminating the distortion caused by the atmosphere and to eliminate the effect on the atmosphere produces images; with this correction physical parameters of the surface of the earth and the reflectance of the surface liang are obtained. Subsequently radiometric calibration, is necessary to produce high quality data chander2009, Landsat 8 images provided by the USGS EROS Center are a series of digital levels that represent data from the spectral image which can be rescaled values of reflectance or radiance on the roof of the atmosphere, TOA using information radiometric provided in the file metadata usgs. The mapping of the guidelines was obtained from three main sources, the first using the Geological-Mining letter F14-7 the Mexican Geological Survey (SGM), the structures reported in this letter were digitized in QGIS QGIS, however the geological map shows a small guidelines density, so the analysis of the structures was carried out using satellite images Landsat 8 provided by the US Geological Survey usgs and satellite images obtained from Google Earth google$_e arthwiththethreesources, amaptha$
$ByusingtheimagesthatGoogleEarthprovides, wehaveaccesstohigher$
$2010-10-29, 2008-11-21 and 2008-11-2. Therefore, onlythecentra$

5 Results

Table 2 shows the results obtained by performing the hypsometric analysis of the basin and their respective sub-basins. We can observe in accordance with strahler1952, the Tierra Nueva can be classified as a equilibrium stage, but it is very near a inequilibrium stage as well; Villela, Lourdes and Carmen sub-basins are in equilibrium stage although Carmen is near to monodnock

Name	Area km^2	H $(mamsl)$	h $(mamsl)$	H_{mean} $(mamsl)$	H_i
Tierra Nueva	1200	2616	1655	2005	0.5728
Jofre	476.5	2544	1655	2016	0.6838
Villela	545	2616	1708	2026	0.5389
Lourdes	47	2129	1660	1820	0.4312
Carmen	126.5	2542	1708	1943	0.3823

Table 2 Watershed and subwatershed hypsometric integral values, Tierra Nueva basin and sub-basins.

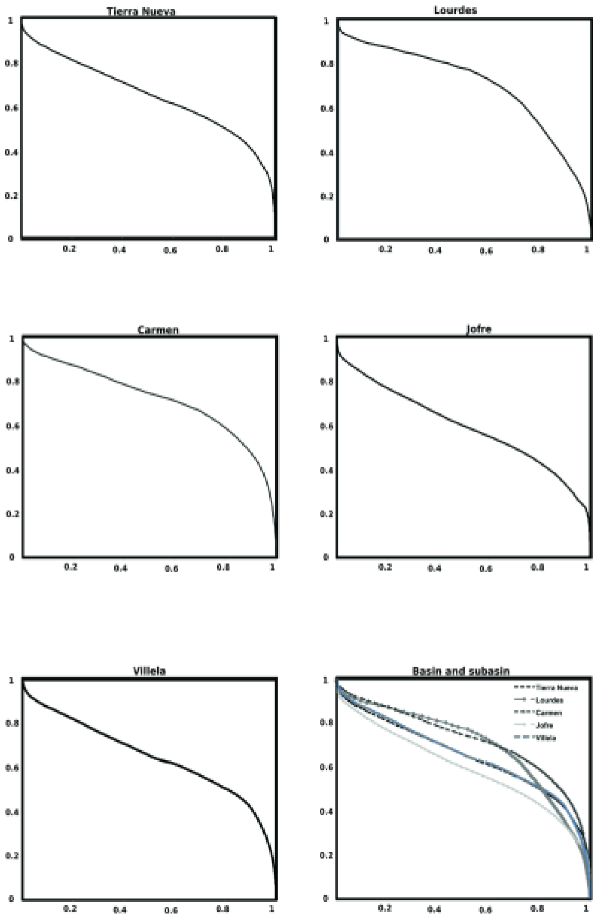

Fig. 5 Hypsometric graphs of Tierra Nueva Basin

phase ritter,gajbhiye. This can indicate Jofre sub-basin as the inequilibrium sub-basin of the system, we must mentions that La Muñeca dam is located in this sub-basin and this zone is more susceptible to be eroded quickly. Villela, Lourdes and Carmen sub-basins are the most appropriate to be considered as areas to implement water management projects because it can only be eroded quickly if there are strong storms that lead to high rates of runoff ritter. Figure 5 shows the graphs of a comprehensive hypsometric. It is possible to appreciate the difference between the states of maturity of each of the sub-basins and the main basin.

With the morphometric analysis done to the Tierra Nueva basin, we can observe that it contains a large

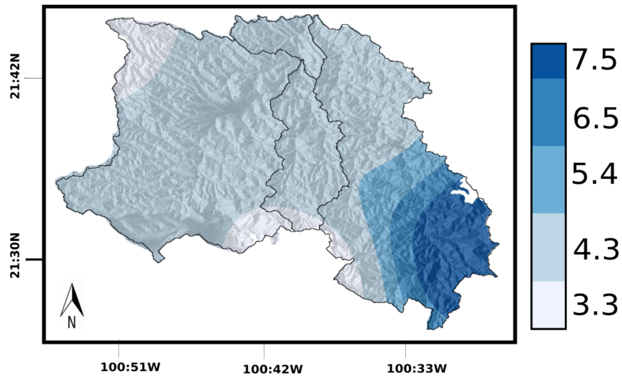

Fig. 6 Periods rain density

number of currents (4714), with orders of currents ≥ 4 and densities of low currents (less than $2km$ per km^2), these parameters according to horton, strahler1957, deju, chirala,golekar provide important information about surface runoff, since the basins with long runoff and low permeability, these parameters coincide with the geological characteristics of the study area reported in the literature noyola2009. In addition to presenting irregular branches that slowly return the flow of water through the surface of the basin. These results show that the study area has little structural disturbance. Both the length ratio current as frequency currents in the study area is considered low, these results tell us that basins and/or sub-basins are in an early stage of developments, that is, even though the area study has been slightly eroded, it is still susceptible to being largely modified. The numerical results of morphometric analysis are shown in Table 3. According to nearing2005 an important parameter to be analyzed when considering erosion is rainfall, especially when the basin is in equilibrium or inequilibrium state. As a consequence this topographical condition is more likely to be eroded by little precipitation. Figure 6 shows the analysis of occurrence consecutive rainfall events within three to seven and half days. This parameter is so important due to the fact that areas with more possibility of catching rain can be observed. Also to determinate that the Jofre basin is structurally the inequilibrium its important to note that this area is where the highest incidence of consecutive rainfall is located, which means that this area is more susceptible to water erosion process. Also the geological structures described by margarito suggests the presences of hard rocks with stuffed fractures. Therefore, the most viable location in which water catchment projects can be implemented is the Jofre sub-basin, this place have the most important density documented rainfall.

Table 3 Morphometric parameters of Tierra Nueva basin and sub-basins

Morphometric Parameters	Units	Values				
		Tierra Nueva	Lourdes	Carmen	Jofre	Villela
Area	km^2	1198.0207	46.9012	126.2463	469.7689	545.8911
Perimeter	km	283.507	54.688	93.694	195.733	187.945
Highest Stream Order	*no.*	6	6	5	4	5
Number Streams	*no.*	4714	125	827	2658	1940
Stream Length	km	1495.6283	61.5765	168.5833	569.4442	695.3215
Drainage Density	km/km^2	1.2484	1.3129	1.3354	1.2697	1.2737
Constant of Channel Maintenance	$no./km^2$	0.8010	0.7616	0.7488	0.7875	0.7851
Stream Frequency		3.9348	2.6652	6.5507	5.6581	3.5538
Bifurcation Ratio		3.84	4.78	4.33	3.28	3.54
Form Factor		0.000535571	0.012369552	0.004442113	0.00144871	0.001129
Circulatory Ratio		0.006730182	0.155440369	0.055821232	0.0189579	0.014188764
Elongation Ratio		0.013056704	0.062748311	0.03760277	0.02147415	0.018957
Total Watershed Relief	km	0.961	1.031	0.834	0.889	0.908
Relief Ratio		0.000642539	0.0167434	0.004947109	0.001561171	0.001305871
Relative relief		0.00064253	0.0167434	0.004947109	0.001561171	0.001305871
Ruggedness Number		0.7697853	0.7852844	0.624531	0.700165	0.712883

Structural Lineament

We carried out the digitization of structural lineaments reported in the letter of SGM. However, there isn't much documented information in this matter. Therefore, we took on the task of digitizing structural lineaments using satellite Landsat 8 image combining bands 6,5,4 and 8,6,3 to observe the land surface. The image of land available in Google Earth was also used; satellite images were superimposed on the CEM 3.0 and with a greater number of these structures. Figure 7 shows the images used for obtaining the structural guidelines and the final product analysis were obtained.
For this study we performed a correlation analysis between the densities of structural lineaments in each subbasin (number of lines per unit area) with maturity obtained through the hypsometric analysis, the correlation we observed between these two parameters is -79% correlation.

Identifying areas of water management

By using morphometric and hypsometric results as well as geology of the area which was sub classified for its hardness, and overlaying network of runoffs, we took on the task of classifying the most suitable areas for the utilization of water resources. Figure 8 shows areas in gray identified as important for water management. The area identified with the number 1 where the flow of Jofre, Villela, and Carmen sub-basins are located. This area can be the most appropriate because in is were the main runoffs of each of the basins converge. Areas 2,3,4 and 5 are in the central part of the Tierra Nueva basin, where a significant amount of runoff converge. In zone 6 which is identified as the most favorable site for a dam to be located. However, La Muñeca dam loses runoffs that are spotted to the northeast of it. We considered that these runoffs should be exploited in some sort of catchment.
Figure 9 shows the area where the "La Muñeca" dam is located. Our analysis matches that it is an appropriate area to implement water catchment. Zone 7 is placed in the south east of the Jofre sub basin part, besides having a significant amount of runoff it is located in the highest areas of the basin and it is also possible to observe that there is the highest density of rainfall analyzed in this study zone.

6 Conclusions

The application of morphometric analysis and morphological analysis within a watershed, and the use of maps of surface runoff to determine the catchment areas together within a GIS provides valuable information to work plan and organize possible hydraulic works. The structural analysis can be useful for such projects.
With regard to planning for future water projects in arid and semi-arid areas. For this zone, it is important to consider that Jofre is a viable option given its morphometric and structural characteristics, it is important to know if is considered a great economical and infrastructural investment. However, the area that we consider the best choice for this study are the Carmen and Lourdes sub-basins, due to being the basins with the most stable morphometry. Further more Carmen has an important area with a lot of runoff lines where hydraulic infrastructure can be built.
It is important to note that the Tierra Nueva basin has been studied as a single basin. The hypsometric results

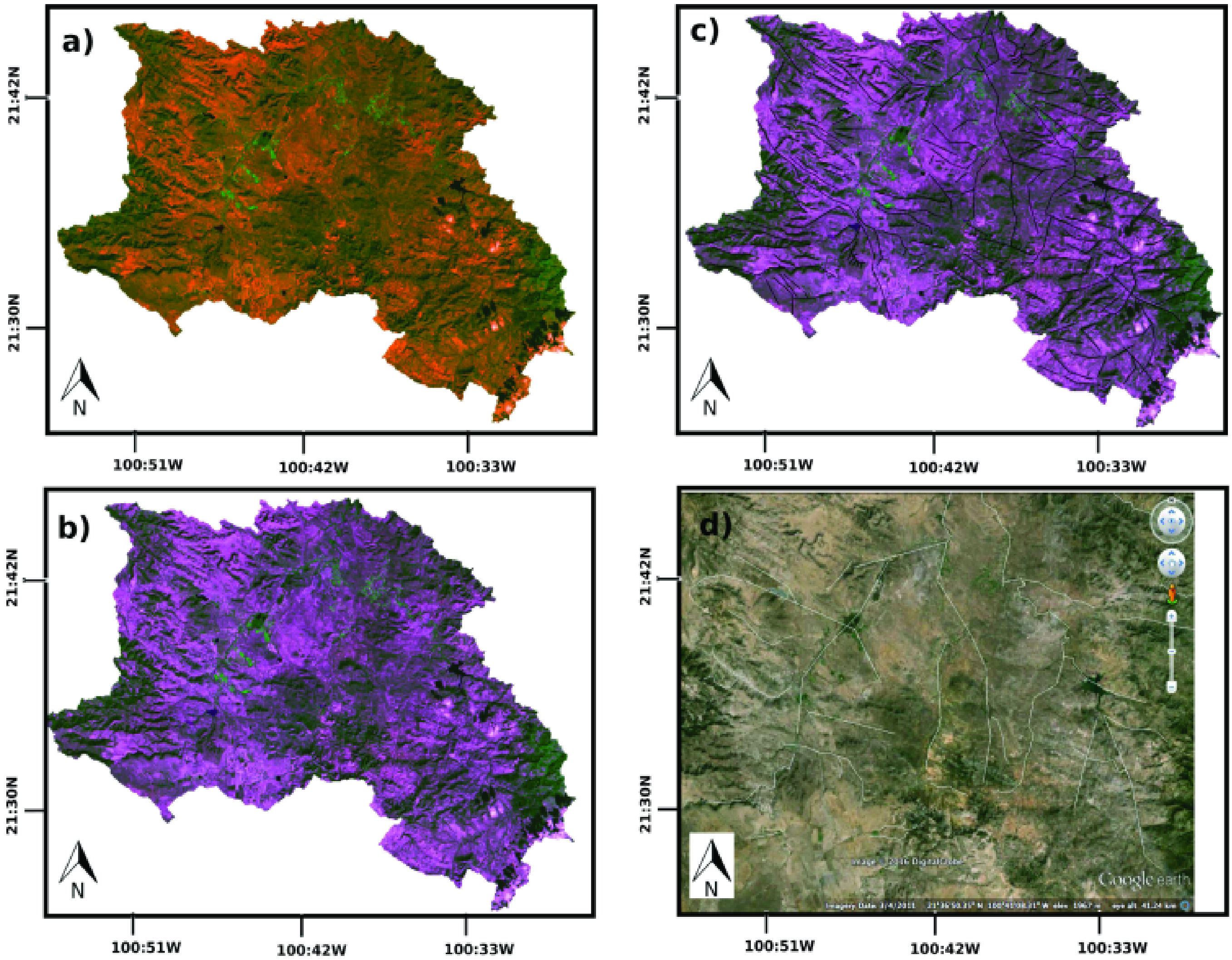

Fig. 7 Images used to structural lineaments. a) Landsat 8 band combination 8-5-2 b) Landsat band combination 8-5-3 c) Structural lineaments obtained from a,b,d d) Image from Google Earth

would have suggested to us that the basin was very close to the status of balance, so it is important when making any morphometric-structural study to consider not only the basin as a unit but also the sub-basins should be considered for individual analysis to make the results more reliable.

Considering the areas that were identified as inequilibrium or little eroded can not necessarily be ruled out for planning hydraulic works but should be considered that these are still susceptible to major progressive changes in their structures due to erosion processes. By geological and morphological parameters can be an advantage for implementing water catchments infrastructure. It is important to note that if we had studied the Tierra Nueva basin as a single basin, the hypsometric results would have suggested that the basin was very close to the status of balance, so when doing any morphometric-structural study this must be done with more detail, considering not only the basin as a unit, but also the sub-basins should be considered for individual analysis to make the results more reliable. As for the areas that were identified as inequilibrium or slightly eroded, we can conclude that there is no need to discard them for planning a hydraulic project, but we must understand that they are susceptible to higher progressive modifications in their structures due to their own erosion system.

The methodology proposed in this work from the integration of hypsometric and morphometric techniques, analysis of precipitation, structural studies of the area of interest and geological parameters, represent a very valuable tool that should be considered for both the planning of hydraulic works, as well as better management of surface water resources, such as flood suscep-

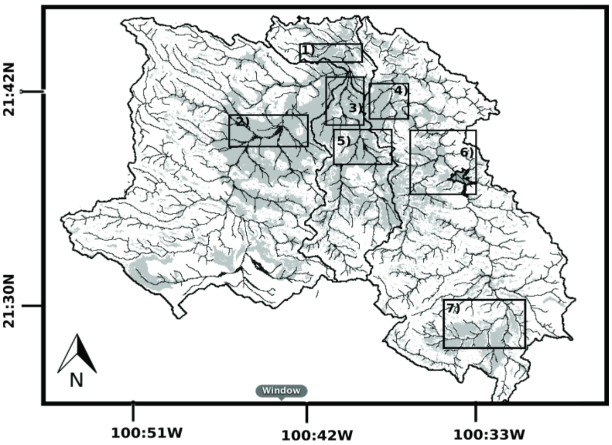

Fig. 8 Location of areas for water collection.

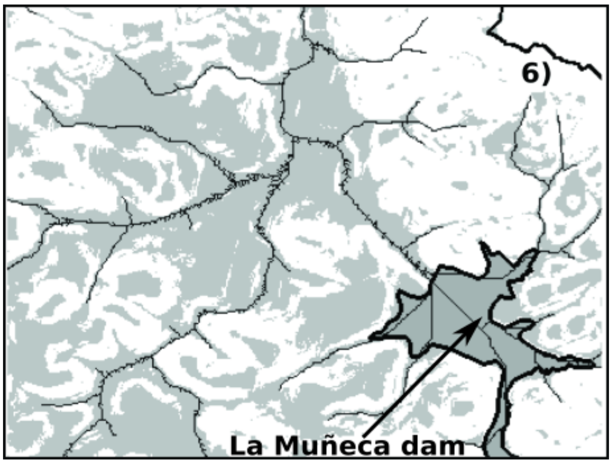

Fig. 9 Simultaneousness between the areas located for water catchment and "La muñeca" dam.

tibility studies and uptake of water resources, among other important aspects.

7 Acknowledgments

The authors would like to thank the editor, associate editor, and anonymous reviewers for their helpful comments and advice.

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Author, Book title, page numbers. Publisher, place (year)