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WATER BALANCE AND LANDSCAPE DEGRADATION OF AN UNGAUGED MOUNTAIN WATERSHED: CASE STUDY OF THE PICO DE TANCITARO NATIONAL PARK, MICHOACAN, MEXICO

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Water balance and its relation to land degradation were investigated by using a spatially distributed model and geographic information system (GIS) in the Pico de Tancitaro National Park, Michoacan, Mexico. The water balance components were defined through monthly climatic data and soil characteristics using ILWIS (Integrated Land and Water Information System) capabilities for the display and manipulation of GIS data. The deficit of water was compared with the potential degradation of the landscape in order to show their relationship. The study shows, in a preliminary way, that land degradation threatens the quantity of water in the Tancitaro National Park. The demand for water has also been increasing to such an extent that it soon will exceed the renewable water supply that can be used economically.

INTRODUCTION

Forest cover helps maintain clean water supplies by filtering freshwater, and reducing soil erosion and sedimentation. Deforestation undermines these processes by degrading the quantity and quality of water supplies (Mulligan, 1998; Bergkamp, 1998). The spatial variability and the diversity of factors that degrade an ecosystem make it difficult to precisely determine relationships; however, it is possible to find tendencies in their relations. One of the most frequent problems in developing countries that face degradation assessment is the insufficient and sparse data. This is the case of the Pico de Tancitaro located in Michoacan, Mexico, in which there are not enough data on water resources. In areas of sparse data, a GIS can be employed in conjunction with a spatially distributed water balance model to assess the availability of water and potential areas of landscape degradation.

A number of authors have carried out similar works about water balance estimates where a GIS plays an important role (Beek, 1996; Ollinger et al., 1998; Mendoza et al., 2002). Also, several examples of estimates of water balance have been performed in ungauged basins (Vandewiele and Elias, 1995; Vandewiele et al., 1991; Xu, 1999).

The analysis of the potential for landscape degradation has been addressed by interrelating slope, soil, and land use (Wang and Takahashi, 1999; Hudak et al., 2001). In general, soil erosion is the most widely recognized and most common form of land degradation (Wischmeier and Smith, 1978; Metternicht, 1996; Sanjay et al., 2001). In recent years, many applications of GIS and remote sensing techniques have been proposed for landscape degradation, although it is clear that new methodologies and algorithms are required for developing countries (Cangir et al., 2000; Feoli et al., 2002). Slope analysis (terrain analysis) has been widely used to understand the dynamics in a watershed (Verstappen, 1983; Verstappen and Van Zuidam, 1991; Goudie et al., 1981; Leopold et al., 1995). Terrain analysis basically allows one to recognize the land units in which a water balance can be computed; thus, zones with deficit or surplus of water can be spatialized.

Both qualitative and quantitative geomorphologic variables have been considered for decades (Goudie et al., 1981).

The main questions that guided this investigation were: (1) what is the annual production of surface water in the Pico de Tancitaro National Park, and (2) what kind of relationships exist between water deficit and potential degradation of the landscape?

The purposes of this study are twofold. The first one is to describe the calculation of a water balance through analytical tools available in a geographic information system, and the second is to establish the patterns of potential degradation of the Tancitaro National Park and its relationship to water balance.

STUDY AREA

The study area (580 km^2) is located in the western part of Michoacan State (Figure 1), in the Neovolcanic Belt. The landscape is a volcanic relief in which the most recent volcano is the 59-yr old Paricutin, and the oldest formation originated 500 thousand years ago. The geology is dominated by andesitic and basaltic rocks, and a number of monogenetic volcanoes surround the stratovolcano (Garduño-Monroy et al., 1999; Scattolin, 1996).

The "Pico de Tancitaro" includes the "Pico de Tancitaro" National Park, which has been declared a priority zone for conservation (CONABIO, 1999; Flores and Gerez, 1994). Elevation ranges from 1300 to 3860 m and the climate is temperate. Annual rainfall is about 1000 mm, from which 80

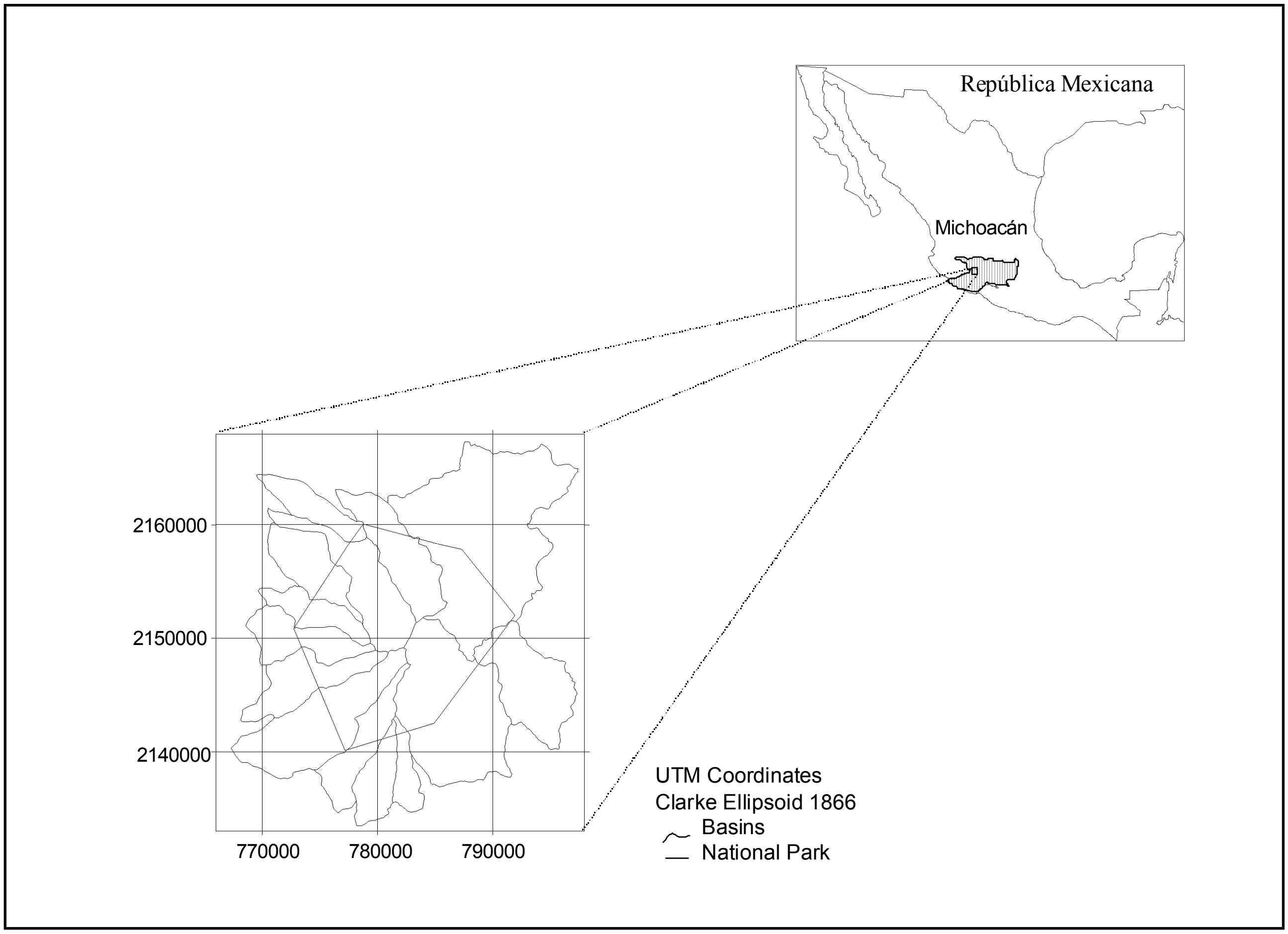

Figure 1. Location of Pico de Tancítaro and its watersheds, Michoacán, México.

percent is concentrated in the rainy season (May to October). Vegetation consists of pine forest, pine-evergreen oak forest, evergreen oak-pine forest, silver-tree forest, cloud forest, secondary vegetation, induced grasses, maize, bean crops and avocado plantations. Intensive land use changes characterize the region since 1970, due the avocado introduction. Subsistence crops, grasses and forest have been removed to establish avocado plantations, which have grown to occupy almost 37 percent of the area in less than 30 years (Bocco et al., 1999; Torres and Bocco, 1999; Fuentes, 2000). The area sustains more than 40,000 inhabitants, most of them indigenous.

METHOD

The method for calculating the water balance is similar to that developed by Thornthwaite and Matter (1955), which includes moisture inputs of rainfall and moisture outputs of runoff and evapotranspiration. The relation is expressed by:

$$Q=P-E-\Delta S \quad (1)$$

where:

Q = Total runoff (mm)

P = Total precipitation (mm)

E = Total evapotranspiration (mm)

ΔS = Change in soil storage (mm)

The water balance is usually used for long periods of time, assuming similar conditions of minimum natural storage (Gregory and Walling, 1985). For periods shorter than a year, the evaluation requires extra care and precision for computing every component. A geographic information system (ILWIS, 1997) was used throughout the entire procedure. To estimate the components of the water balance the relations given by Beek (1996) and Serruto (1993) were used (Table 1).

Table 1. Equations Used to Obtain the Water Balance Components

Component	Equation	Author
Potential Evapotranspiration	$PEt_m = (0.003*(RS)^{2.5}+0.16*(T_m)^{0.88})*31$ (2)	Serruto (1993)
Actual soil moisture storage	$S_{(a)m} = (P_{(ef)m}+S_{(a)month-1})-PEt_m$ (3)	Beek (1996)
Actual Evapotranspiration	$Eta=P_{(ef)}+S_{(a)month-1}$ (4)	Beek (1996)
Water Deficit	$WD=PEt_m-(P_{(ef)m}+S_{(a)month-1})$ (5)	Beek (1996)
Surplus Water	$SW=P_{(ef)m}-Eta_m- S_{(a)m}+ S_{(a)month-1}$ (6)	Beek (1996)

where:

Pet_m = Potential evapotranspiration (mm)

RS = Solar radiation in equivalent units of evaporation (mm/day^{-1})

T = Temperature (^0C)

$S_{(a)m}$ =Actual soil moisture storage of current month (mm)

$S_{(a)month-1}$= Actual soil moisture storage of previous month (mm)

$P_{(ef)m}$=Effective precipitation (mm)

Eta =Actual evapotranspiration (mm)

Land variables

Elevation, rock and soil types (FAO's classification), and maps at a 1:50,000 scale were digitized from analog maps produced by the National Institute of Statistics, Geography and Informatics of Mexico (INEGI by its acronym in Spanish). The landform map and land use cover (Figure 2) was obtained through geomorphologic photo-interpretation, digitization, and ortho-rectification of aerial photography at a 1:50,000 scale (Fuentes, 2000). Soil stoniness and soil texture maps were derived from INEGI's soil maps and from soil surveys as attribute maps. A digital elevation model was created from the topographic map; slope maps were derived for each of the 16 sub-catchments.

Temperature and precipitation

The primary data sources for temperature and rainfall analyses were the monthly mean values from 13 meteorological station records covering the period from 1970 to 1985 (Figure 3, Table 2). Temperature and precipitation maps were created by using the linear interpolation method that gives better estimation of rainfall surfaces than the Thiessen polygons in mountainous areas (ITC, 1999). Each one of the 12 maps obtained for both variables was corrected by altitude (Agricultural Compendium, 1981; García, 1984).

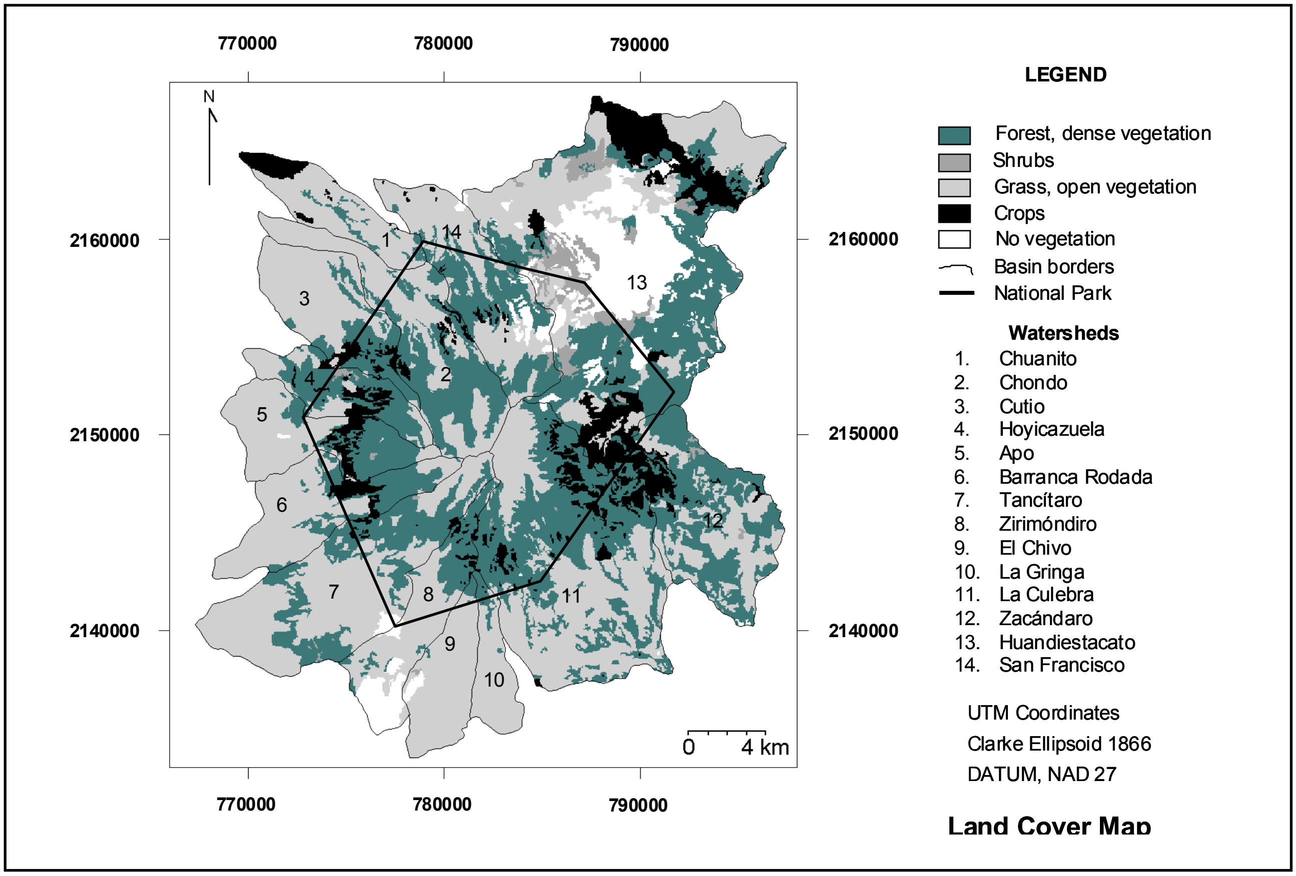

Figure 2. Land cover map (source: photo interpretation).

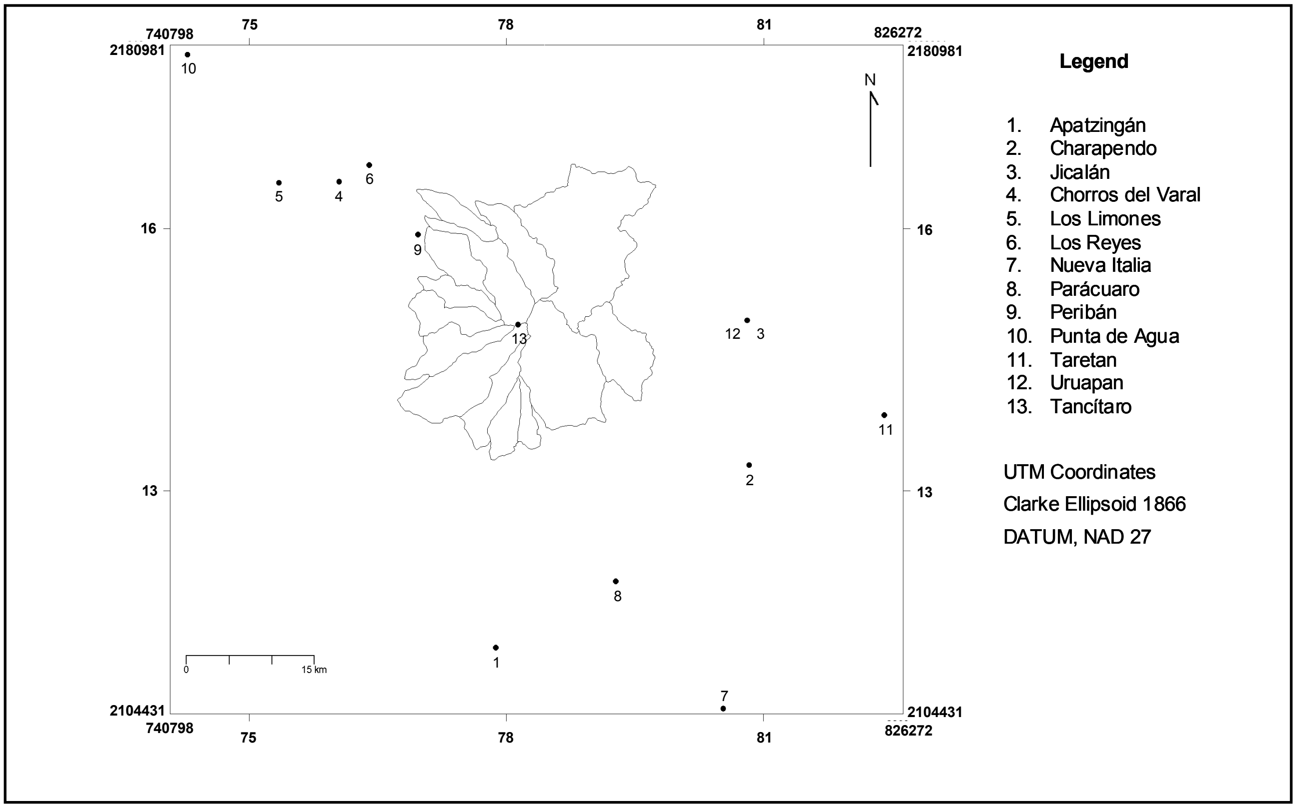

Figure 3. Meteorological station map.

Table 2. Temperature (T) and Precipitation (P) Mean Values, in Thirteen Stations Inside and Bordering the Study Area

Station	Altitude	P	T		Station	Altitude	P	T
1. Apatzingan	320	836	27.4		8. Paracuaro	498	1003.2	25.7
2. Charapendo	1000	1196.3	22.6		9. Periban	1630	1255.2	19.7
3. Jicalán	1610	1502.8	17.8		10. Punta de agua	279	686.4	27.8
4. Chorros del Varal	1225	946.2	23.9		11. Taretan	1170	1165.7	22.3
5. Los Limones	1225	1042.7	20.9		12. Uruapan	1610	1584.8	19.5
6. Los Reyes	1280	860.9	20.7		13. Tancítaro	3800	910.5	8.3
7. Nueva Italia	460	705.5	26.3					

Potential Evapotranspiration (Pet)

Pet was calculated on the basis of the equation of Serruto (1993); the average monthly temperature and the solar radiation were adjusted according to latitude values (FAO, 1976). This formula was selected for its simplicity and efficiency instead of the Blaney and Criddle (FAO, 1976), the one of Thornthwaite and Mather (1955), or that of Penman (FAO, 1976). Serruto's formula calculates the potential evapotranspiration according with Equation 2 (Table 1).

Runoff and effective rainfall

Runoff estimation was derived from reclassified maps of infiltration, slope and vegetation, using the data values given by the Soil Conservation Service (1964). The procedure consisted of creating a two-dimensional table, which allows one to obtain reclassification values. Afterwards, each reclassified map was multiplied by each monthly precipitation map to finally create a monthly runoff map, whose values were expressed as percentages. To do this it was assumed that infiltration rate, slope, and vegetation values were constant through the year.

Available rainfall was the difference between precipitation and runoff on a monthly basis.

Maximum soil moisture storage

When rainfall penetrates the soil, a portion of it is stored in the pore spaces, while the remainder drains downward. The water stored in the soil is the source that might be available for evapotranspiration (Beek, 1996; Birkeland, 1999). However, soil moisture content varies according to soil texture and stoniness as shown by Landon (1984). In this study the data values obtained by Landon were used, assuming a root penetration depth of 100 cm. As mentioned above, texture and stoniness maps were generated from soils maps published by INEGI, at 1:50000 scale, and direct field measurements. Based on those data, soil maps were reclassified and crossed through a two-dimensional table in which the Landon values were assigned. These values were used to determine the real storage values for the first month of the water balance.

It is necessary, however, to keep in mind that soil layers with variations in texture, porosity, depth, etc., affect the water movement and therefore, the soil moisture storage. For this reason it is highly recommended to evaluate the soil moisture storage directly in the field.

Actual soil moisture storage ($S_{(a)m}$)

The actual soil moisture storage varies in time according to the inputs (effective precipitation) and outputs (e). Thus, it is necessary to reflect monthly moisture variations considering that the previous month could store water if rainfall was more than normal; then, for the following month there could be some water storage in the soil. Evapotranspiration has an opposite effect and it becomes critical if the effective precipitation has diminished or its contribution is zero. The actual storage was calculated by Equation 3 (Table 1) utilizing the maximum storage capacity as was mentioned above. The calculations are started after the dry season (when P>Eta) at the month that presented soil moisture. In this case, June is the first rainy month.

Actual Evapotranspiration (Eta)

We describe actual evapotranspiration as the quantity that plants and bare soil really evaporate. The actual evapotranspiration depends on storage, effective precipitation and potential evapotranspiration of previous month. If there is enough water to evaporate, Eta=Pet, otherwise Eta<Pet. The actual evapotranspiration was calculated by Equation 4 (Table 1).

Monthly water deficit (WD)

Water deficit occurs when the evapotranspiration is higher than the effective precipitation (Morales and Saavedra, 1998; Beek, 1996). The water deficit was calculated by means of Equation 5 (Table 1). The calculations began in June, and for every month a map was made.

Monthly surplus water (SW)

When the effective rainfall is higher than evapotranspiration, an excess of water occurs because the soil water content increases to the maximum storage capacity. The water surplus was calculated using Equation 6 (Table 1). Twelve maps of surplus water were obtained.

Annual water balance

Monthly deficit maps are added together to obtain an annual deficit map. The same is done for monthly surplus maps (Figures 4 and 5). These maps were reclassified in several classes in order to

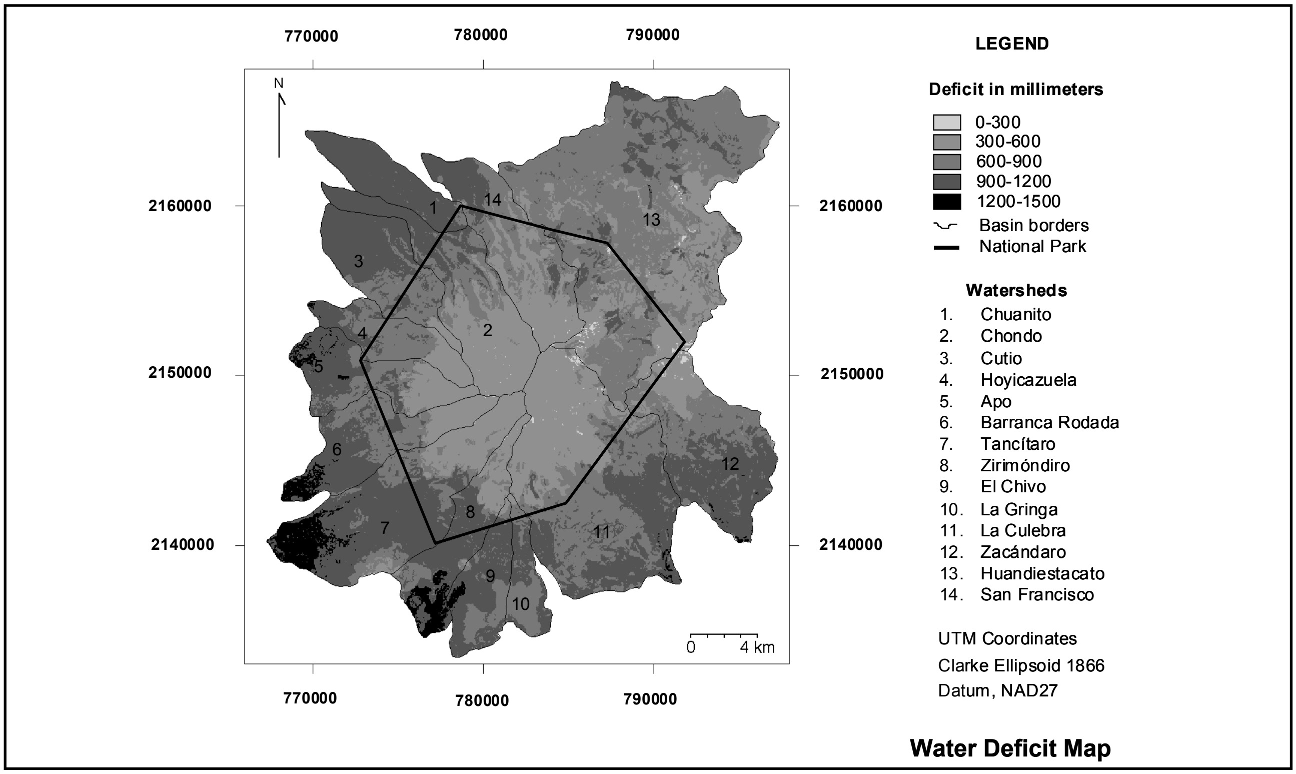

Table 4. Water deficit in the Tancítaro Region.

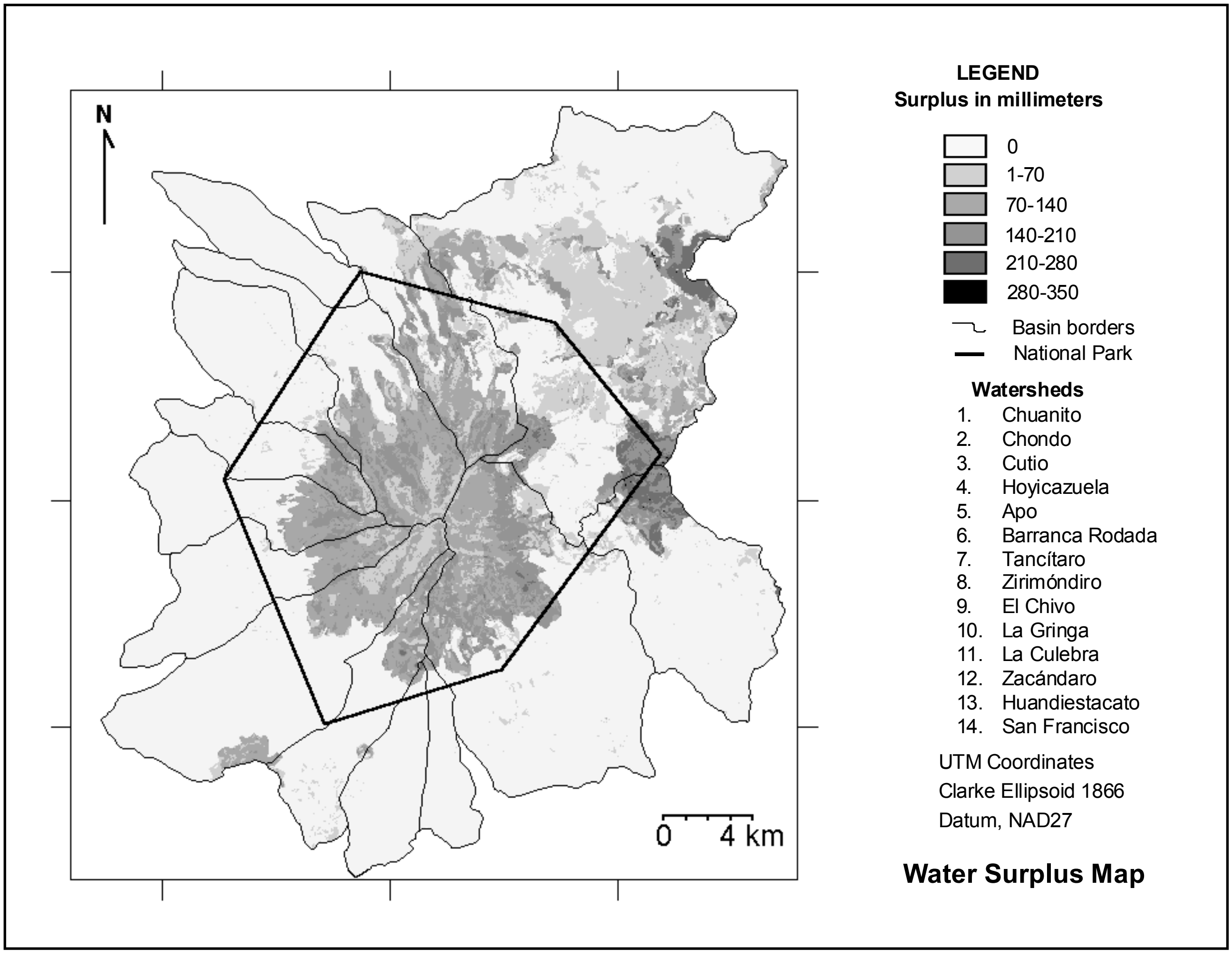

Figure 5. Water surplus in the Tancítaro Region.

be clear. Water deficit classes include: very high (1200-1500 mm), high (900-1200 mm), moderate (600-900 mm), low (300-600 mm) and very low (0-300 mm). And water surplus: very high (280-350 mm), high (210-280 mm), moderate (140-210 mm), low (71-140 mm), very low (1-70 mm) and no surplus (0 mm).

Degradation map

This map was obtained by means of photo-interpretation, digitization, and ortho-rectification of aerial photography at a 1:50 000 scale. Areas were identified with poor vegetation cover, the presence of gully erosion, and slope and soil erosion susceptibility. This step was calibrated through verification points in order to obtain five classes of potential degradation: a) no apparent degradation, b) incipient degradation; b) moderate degradation, c) advanced degradation; d) severe degradation, and e) conservation zone (Figure 6).

A theoretical model of potential degradation was obtained from the degradation map (Figure 7). The spatial dynamics of the degradation is similar to the dynamics observed in the surplus and deficit water. At higher altitude there is less degradation. However, this pattern changes at 3000 m due to natural conditions such as fragile and superficial soils, and open forest.

In order to analyze degradation and water balance relationships, a first step was to compare runoff with degradation data per basin; a second step was to compare degradation with deficit and surplus water values for the whole region.

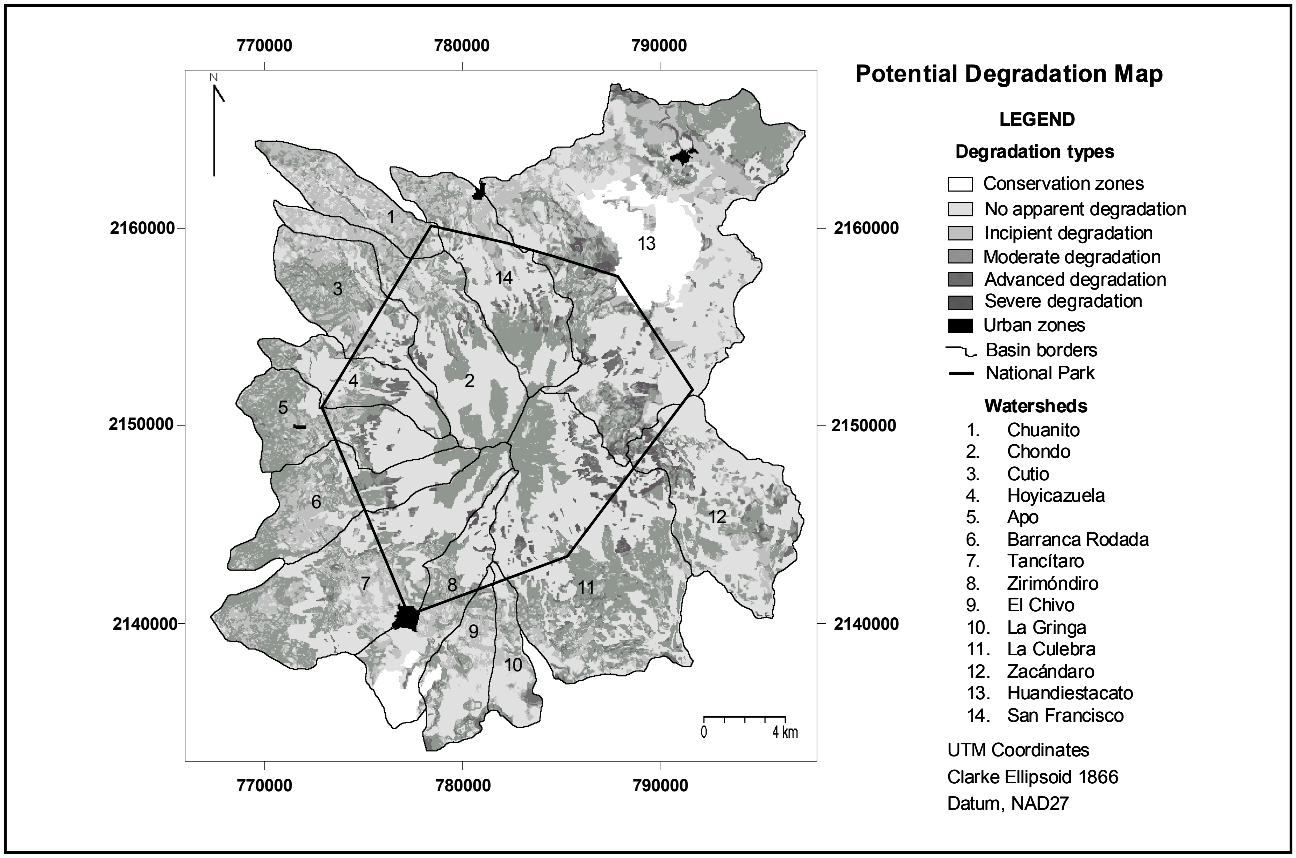

Figure 6. Potential degradation in the Tancítaro Region.

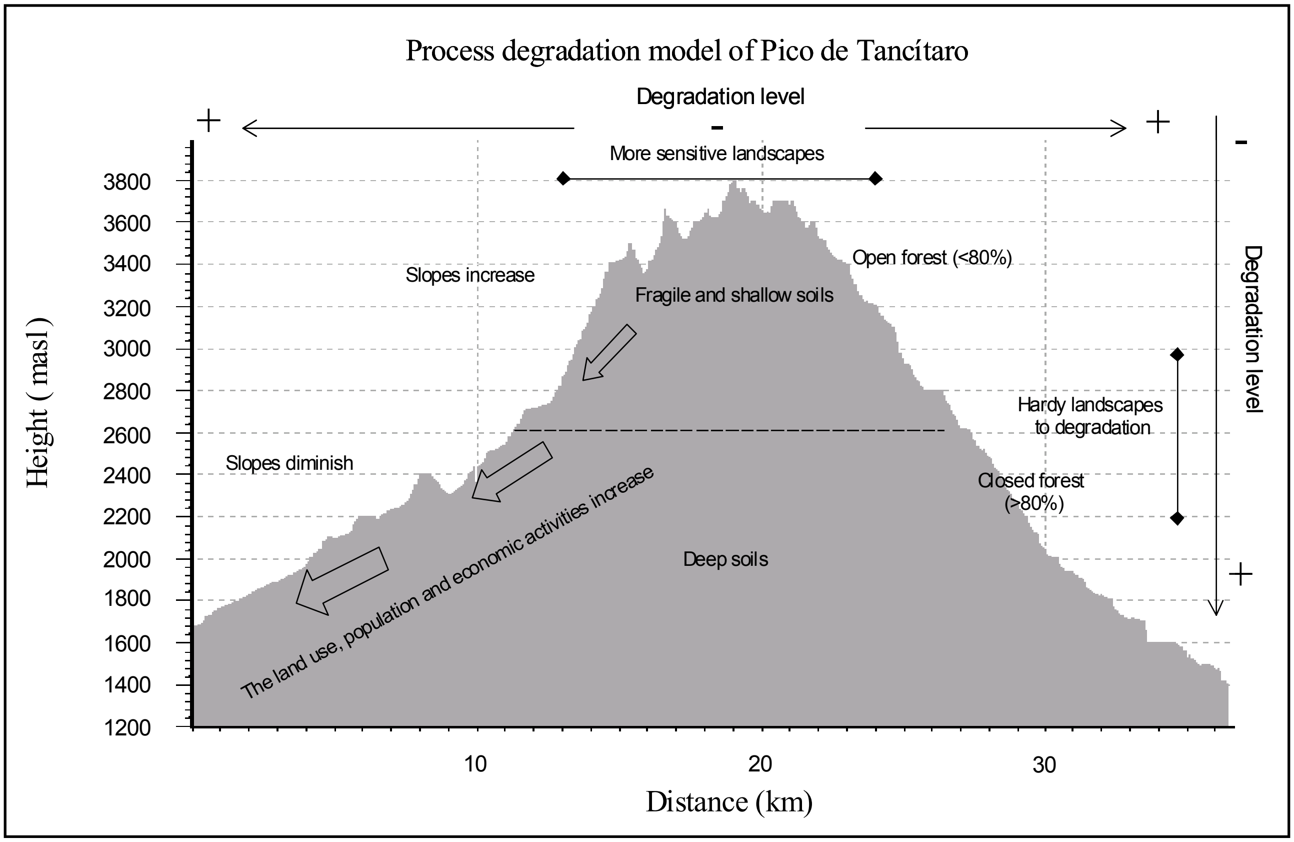

Figure 7. Descriptive model of potential degradation in the Tancítaro Region.

RESULTS AND DISCUSSION

Deficit and surplus water

Figures 4 and 5 show the deficit and surplus water maps. In the first map, values of water deficit increase at lower altitude, because of intensive land use for avocado plantations. In the second map, the spatial pattern of surplus water increases with altitude, because of better vegetal cover. Observing both surplus and deficit water maps, the Pico de Tancitaro National Park had a negative water balance. According to UNESCO (1999), this condition is normal for Mexico.

Runoff and degradation

Table 4 shows runoff estimates per basin. The higher runoff values correspond to Chuanito and Chivo basins and the lowest values to San Francisco and Chondo basins. The former basins had high runoff values and poor vegetal cover, and a large degradation tendency (such as Cutio, Chondo and Rodada basins). On the contrary, San Francisco and Chondo basins present a good natural cover and larger surface with no apparent degradation.

Table 4. Natural Cover, Land Degradation, and Runoff Comparison by Basins

Watershed	Natural cover (%)	Land degradation (%)	Runoff (mm)
Apo	56.8	64.3	483.8
Chondo	64.2	49.5	405.7
Chuanito	18.2	76.7	615.3
Cuenca Rodada	42.0	68.4	474.1
Cutio	31.2	66.4	563.4
El Chivo	15.7	50.6	609.1
Hoyicazuela	66.6	44.1	453.9
Huandiestacato	60.7	46.1	493.7
La Culebra	57.2	51.6	477.8
La Gringa	18.1	44.2	573.6
San Francisco	59.4	54.3	399.0
Tancítaro	53.7	56.9	488.5
Zacándaro	60.9	42.5	576.8
Zirimóndiro	36.9	39.8	539.3

Relation between water resources and land degradation

Generally speaking, a tendency is observed in Figures 8 and 9 in which water deficit is related to landscape degradation. It seems that the use of models in ungauged basins makes it possible to discover, at least in a preliminary way, some trends in the status of natural resources. It is also necessary to indicate that the applied model is empirical and includes assumptions that should be tested under local field conditions. In spite of this, this study has made it possible to establish a profile of the relationships between the availability of the hydrological resource and landform degradation in the Tancitaro National Park.

CONCLUSIONS

The study area presents a water deficit character. The areas with vegetation cover yield enough water to supply the lower areas, which demand excessive water for avocado plantations. In general, the areas with evident degradation are linked to the zones with high deficits of water. This should be

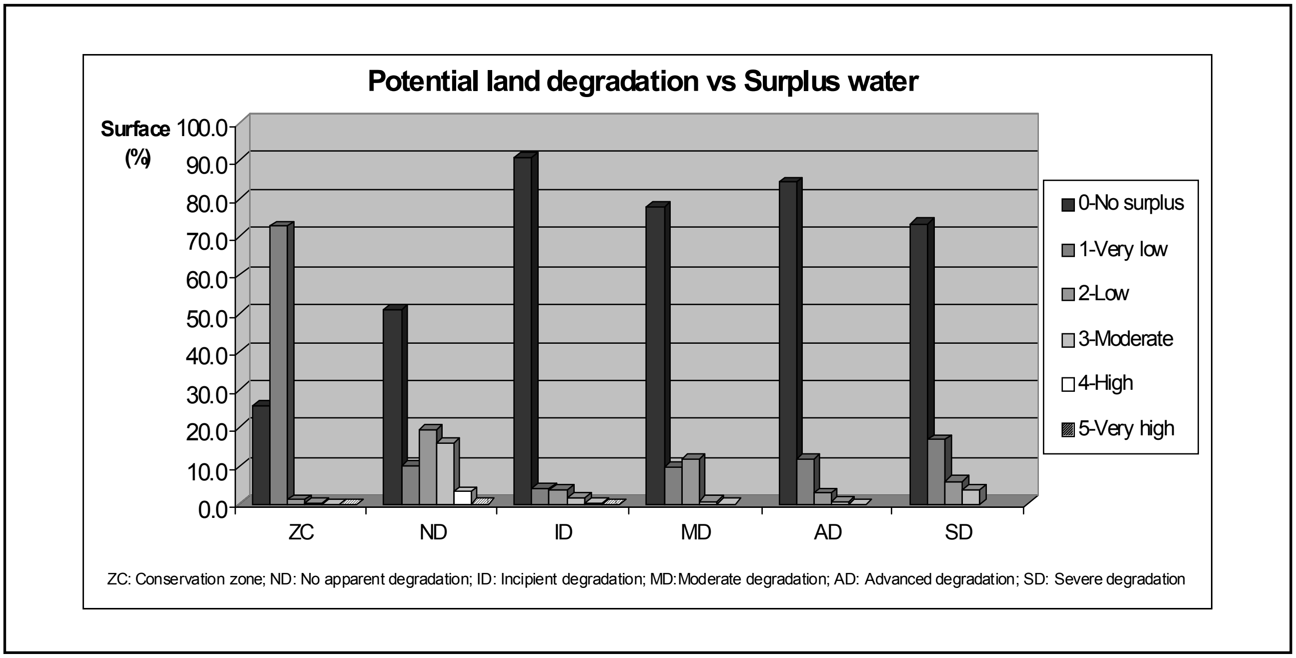

Figure 8. Potential land degradation vs surplus of water.

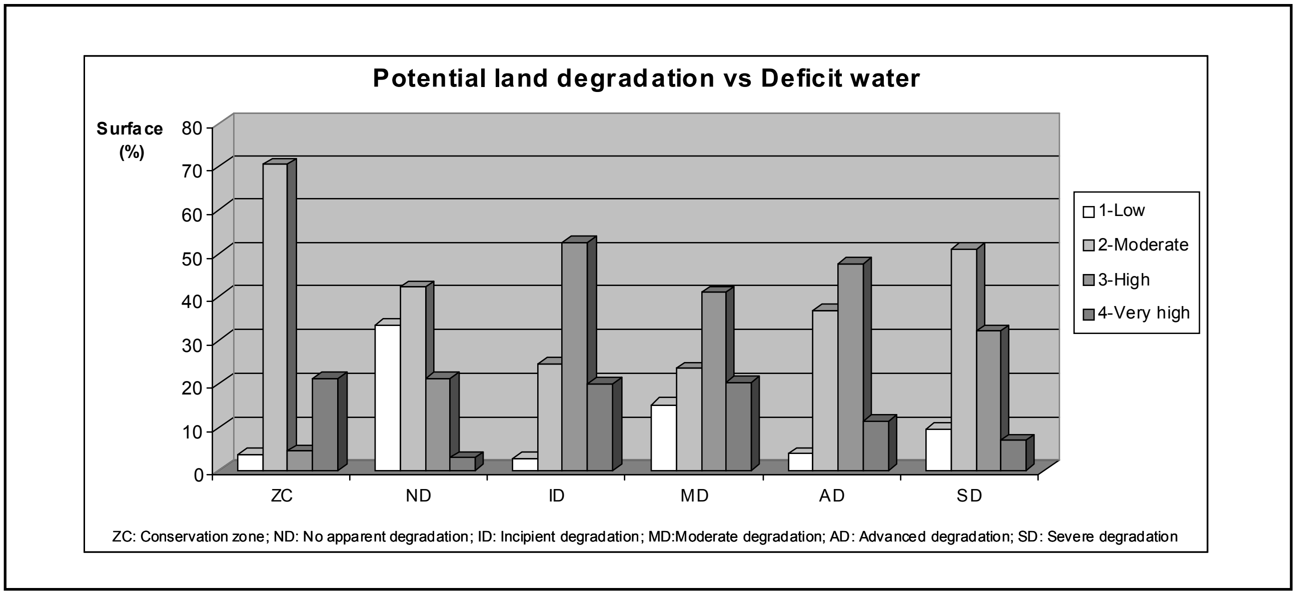

Figure 9. Potential land degradation vs deficit of water.

considered as a preliminary conclusion and therefore should be taken with caution. It seems that the demand of water has been increased to such an extent that it soon will exceed the renewable water supply. This observation is based on the large diversions of surface water, particularly for avocado irrigation.

The National Park should be mainly preserved to insure its hydrologic role: provide the basic goods and essential natural functions such as air and water filtering. An equally important effort is needed to motivate local communities and individuals to adopt an ecosystems approach to managing this valuable environment. In practice, this requires not only understanding of the complexity and resilience of the ecosystem, but also a reorientation of our usual extractive approach. Mankind depends on ecosystems to sustain it, but the sustainability of the ecosystems depends, in turn, on human care.

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