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Evaluation of total runoff for the Rio San Pedro sub-basin (Nayarit, Mexico) assessing their hydrologic response units

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Abstract

The Rio San Pedro sub-basin runoff was estimated using the curve number method (NRCS-CN) applied to hydrologic response units (HRU's), derived from remote sensing and GIS analysis. The sub-basin (around 2900 km^2) was delineated from digital elevation models (DEM), that also were used to obtain the slopes in the study area. A landscape characterization (overall accuracy > 80%), based on Landsat ETM+ imagery, was obtained using standard classification methods, and together with a rainfall data series, were the input information for the sub-basin discretization in HRU's and the runoff calculation. Seventeen HRU's were obtained, that can be arranged in three main groups. HRU's associated to forest and high relief areas, representing 2/3 of the total area and contributing up to 71% of total runoff. The land covers related with human activities integrate a second HRU's group, contributing with 20% of runoff, although they represent less than 15% of the area. Finally wetlands and aquatic surfaces, not contributing to runoff, are the third HRU group. Because of the measures of accuracy correspond to good agreement between the model and the reference data, the HRU's approach that retains the spatial heterogeneity, is considered a fine approximation for the San Pedro sub-basin runoff assessment that can be integrated to the development of environmental management programs.

Key words: Runoff, hydrologic response unit, curve number, land uses, GIS, DEM.

INTRODUCTION

Spatial variability in characteristics and parameters controlling physical, hydrological and biological processes is a common feature of land surfaces, so it has to be considered for hydrological modeling (Becker and Braun 1999; Tokar and Markus, 2000). Since responses from hydrological processes are sensitive to the scale of the analysis, different levels of regionalization are needed at different scales, and furthermore, it is important to test the hydrological models at several scales.

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The basin and sub-basin scales are considered as the most natural partitioning of the terrain as natural boundaries (topography) and hydrology define them, but the incompleteness of our understanding of the heterogeneity of watershed attributes and processes is a limiting factor in applying physically based models. Spatially distributed hydrologic models are often applied to represent the catchment dynamics, to assess the impact of land use practices and to test hypotheses on the hydrological functioning of basins (Haverkamp *et al.,* 2005; Lazzarotto *et al.,* 2006). Models can be used as effective tools to predict environmental costs of land use changes on the hydrologic system, as simulation of different scenarios can be integrated to the models to analyze the scope of decisions for the basin's management and to optimize the functions of landscapes (Fohrer *et al.,* 2002).

However, when the spatial data used for modeling is aggregated from the scale of measurement to the scale of model resolution, the heterogeneity within sub-basins may be lost with respect to soil, vegetation, land use and other factors. Reducing the size of the study area to maintain the effect produced by these heterogeneities is considered not a practical solution (Sophocleous and Perkins 2000). Data aggregation might eliminate the information relevant at the particular model scale and the accuracy of parameterizing the small-scale variability is partially lost when physiographic information is aggregated or generalized. One option and a practical alternative for including spatial information and the effects of these heterogeneities is to structure the catchment into subunits of similar hydrologic dynamics, commonly referred to, among others, as Representative Elemental Areas (REA) by Wood et al. (1988); Grouped Response Units (GRU) by Kouwen et al. (1993); Hydrologically Similar Units (HSU's) by Schultz (1996); Hydrotopes by Meijerink *et al*. (1999); or Hydrological Response Units (HRU's) by Leavesley *et al*. (2002). The central idea for each one of these concepts is that areas exist with a relative uniformity of characteristics, such as slope, elevation, vegetation, soil type and geology, among others, that produce similar output responses (runoff, evaporation) to the hydrological input (rainfall). For the purposes of the present study, the term HRU was accepted to define such areas.

Delineation of the watershed subunits is an important discretization step previous to the modeling, and it can be achieved with the aid of remote sensing (RS) and geographic information systems (GIS). It is useful particularly where discharge time series are insufficient for hydrologic modeling. Development of HRU's as modules with unique combinations of physiographic properties allows the preservation of the heterogeneity of the drainage basin and thus can be used for further divisions retaining the topographic inputs and also making possible regional hydrological modeling (Flügel 1995, Sophocleous and Perkins 2000). The basin mean hydrologic response is then assumed as the mean of each hydrologic component weighted by area (Sophocleous and Perkins 2000), and also can be evaluated as the total basin response, which is the summary of responses of all HRU's, weighted by area (Leavesley *et al*. 2002). The latter approach was adopted here.

Taking into account that hydrologic time series are limited in Mexico, there is a strong need for hydrologic modeling tools that can be used to assess the effects of land use on the hydrologic cycle at a watershed scale with the available information. These hydrological models developed at a basin scale are required to improve the water resource management, which is a critical issue in most parts of Mexico.

The objective of the present study was to evaluate the runoff, one of the output components of the hydrologic balance, in the low sub-basin San Pedro (Mexico), based on information provided by earth observation satellites, digital elevation models (DEM), rainfall data and field and ancillary data, using GIS tools within a semi-distributed hydrologic model approach.

STUDY AREA

The study area includes the lower Rio San Pedro sub-basin, located in northwest Mexico at the Hydrologic Region RH-11 (Presidio–San Pedro), covering a surface about 3000 km^2 (Figure 1). It is in the end of the San Pedro - Mezquital watershed, which embraces an area estimated at 26,000 km^2, being one of the most important in northwest Mexico. This basin has its origin in the plateau of Durango state, in the Sierra Madre Occidental, where pine and pine-oak forest are the most relevant vegetation types, under pressure because of intensive logging, overgrazing and road construction. The average elevation is around 2000 m above sea level, and river runs to the south, crossing the Sierra Madre, to become into San Pedro River in Nayarit State. The region displays different climate types, from temperate and semi-cold climates in the higher grounds, to sub-humid warm in the lowlands, where tropical sub-deciduous and tropical dry forests are dominant. The river flows to the Pacific Ocean through the state of Nayarit, where it changes direction to the west, covering the sub-basin about 16% of the surface of this State.

In the study area the land covers are defined by an altitude gradient, with tropical sub-deciduous in the higher parts (> 100 m above sea level), representing around 60% of the total study area. This is followed by agriculture (tobacco, cane sugar, grains and vegetables) in the middle of the floodplain, and wetlands (saltmarshes, mangroves, estuaries) to the coast. Because of the very flat topography of the downstream part (< 20 m), the river's course is not well defined and it joins to a complex lagoon system, with Laguna Grande de Mexcaltitán, Estero Grande, Las Gallinas, Macho, El Tanque, and El Mezcal, as the most representative (INEGI 1999). The soil types are mainly Regosol, Cambisol and Fluvisol, that together amount around 60% of the total area.

Inside or close to the study area, there are 11 meteorological and hydrometric stations that provide with information on rainfall and hydrology of the river. From these, an average of 2735 million m^3 yearly (measured at the San Pedro hydrometric station) is estimated. It has a laminar flow calculated at 106 mm and a runoff coefficient of 7.9%. The San Pedro sub-basin has an annual rainfall of 700 to 2000 mm, with a rainy season that varies from June until mid-December, having little or no rainfall the rest of the year.

METHODOLOGY

To achieve the aimed objective, some steps were followed: First, boundaries of the sub-basin were defined and the river network was extracted, with special attention to the flat areas. Second, a landscape characterization, satellite imagery based, was produced for the study area. Third, discretization of the study area, defining the HRU's and Hydrologic Soil groups (HSG) with the slope, land cover and soil types as input data. Finally, the runoff was estimated using rainfall data as input and the Curve Number method (USDA 1986) for the final assessment, evaluating runoff at HRU and sub-basin level.

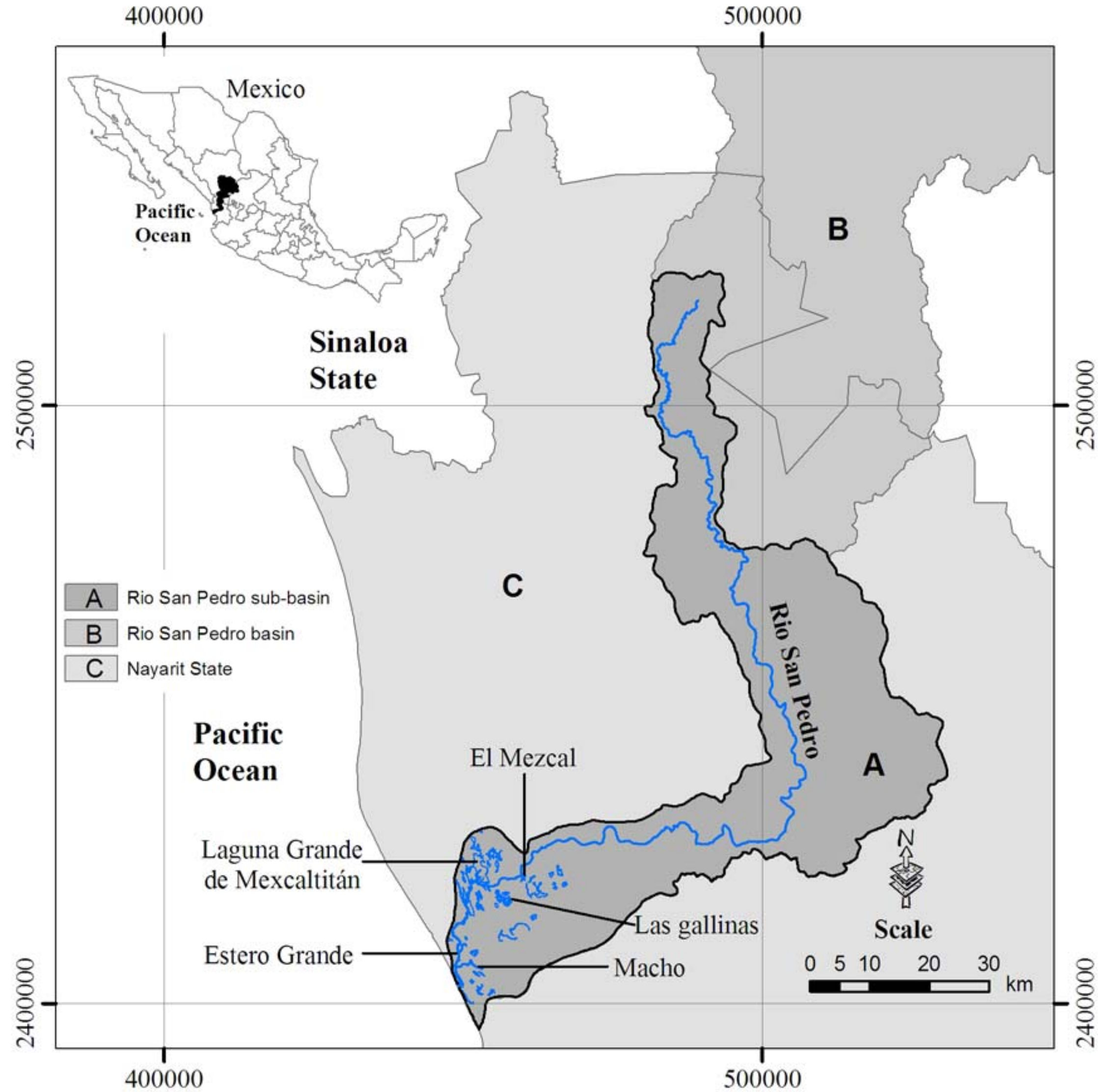


Figure 1. Geographical location of the Rio San Pedro sub-basin, Nayarit, Mexico.

Watershed delineation

Procedures for extracting topographic features and drainage network and to delineate basins and sub-basins are extensively described in the literature, with discussions on the potential and weaknesses of different approaches (O´Callaghan and Mark 1984; Jenson and Domingue 1988; Montgomery and Dietrich 1992; Garbrecht and Martz 1997; Tarboton, 1997; Martz and Garbrecht 1998; Turcotte *et al.,* 2001),

For the purposes of present study, the Spatial Analysts tool and Arc Hydro Tool for ArcGIS 9.0 were employed to extract topographic features and to delineate the sub-basin map from digital elevation models (DEM´s). Major problems were related to delineate the drainage network in flat areas, where automatic extraction of streams often does not coincide with mapped streams.

Because of a large proportion of the coastal plane in the study area is relatively flat, with altitudes <2 m above mean sea level, the "stream burning" technique was used to force drainage along known river channels in flat areas. This approach uses a rasterized version of a vector hydrographic map to reduce the relative elevations of streams pixels to a uniform depth. (Maidment 1996).

Previous selection of hydrographic features corresponding to hydrologically connected stream channels was done and the stream maps were converted to single-cell strings in raster format, assigning an elevation value of 1 m, while off-stream pixel elevations were increased by 1 m and areas such as ocean and elevations > 50 m were masked assigning them a 0 value. DEMs with 50 m horizontal resolution (UTM projection, Datum NAD27) and 1 m vertical resolution (Vertical Datum NAVD29). were used. After they were modified, a pit-filling algorithm to eliminate natural depressions from the analysis (Jenson and Domingue 1988) and a D-8 algorithm to calculate flow direction (O'Callaghan and Mark 1984) were applied, attaining the river network as final output (Saunders 1999).

Landscape characterization

The landscape characterization was derived from Landsat ETM+ images, using the procedures described by Ruiz-Luna and Berlanga-Robles (1999), Alonso-Perez *et al.* (2003) and Berlanga-Robles and Ruiz-Luna (2002) for neighboring areas. Three Landsat scenes, acquired during the 2001 dry season, were used to to produce the land cover/uses map by means of the histogram-peak unsupervised classification technique (Eastman 2003). The spectral classes derived from this procedure were reclassified into seven main informational classes, depending on their spectral response (Aquatic surfaces, Mangrove, Saltmarsh, Agriculture, Secondary succession, Forest, and Exposed soils). An additional class representing Villages, previously digitized on-screen using the panchromatic channel, was added to the final output.

The accuracy assessment of the thematic map was assessed with an error matrix using columns as the reference data (obtained in field surveys), and rows with results from the classification. In this array, the elements in the main diagonal represent coincidences among classification and reference data. The overall accuracy of the classification is then calculated from this matrix (the sum of the elements on the main diagonal divided by the total number in the sample), an also the individual accuracy for each class is calculated as the producer´s and user´s accuracy (Congalton and Green 1999). Finally, an estimator of the Kappa coefficient (^K), that statistically determines whether an error matrix is significantly different from another produced by the chance, was obtained. The ^K is a measure of agreement between the classification and reference data, after removing the proportion that could be expected to occur at random (Yuan et al., 2005). The ^K values range from 0 (null agreement) to 1 (total agreement), and here the output classification was accepted when ^K ≥ 0.8, corresponding to a measure of the relative strength of agreement labeled as substantial to almost perfect, in the scale proposed by Landis and Koch (1977). The reference data used for the accuracy assessment were recorded in the study area with the aid of a GPS (< 15 m accuracy) and at least 30 test points per class were taken from the data base through a stratified random sampling scheme. A flow diagram with the process followed to obtain the final thematic map is shown in Figure 2.

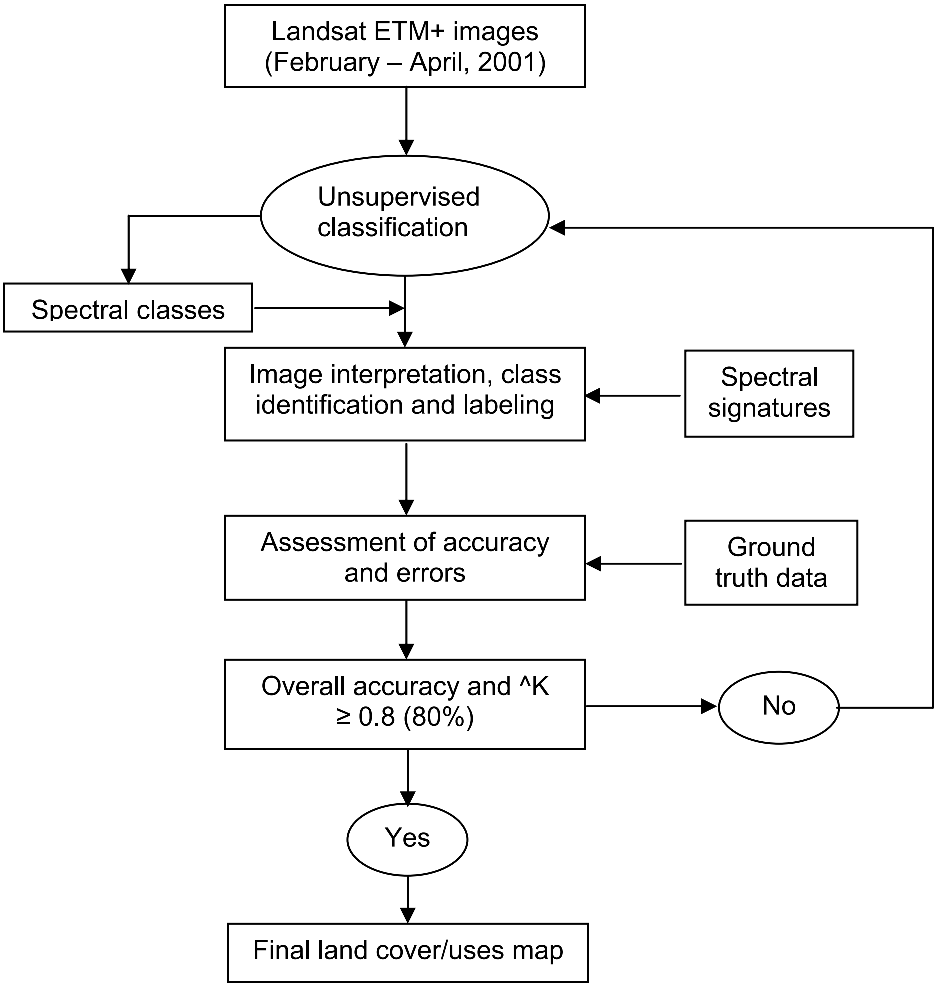


Figure 2. Flow chart of land cover classification

Watershed discretisation

Once the boundaries and landscape characteristics of the San Pedro sub-basin were defined, the study area was discretised into polygons internally homogenous, taking the slope and land use/cover as primary elements for the HRU's partition. Slopes in the study area were derived from DEM's (1:50 000) using extraction topographic features techniques and they were sorted in four slope classes: a) < 10°, b) 11°- 20°, c) 21° - 40 ° and d) > 40°.

For this analysis, the land cover categories aquatic surfaces, saltmarsh and mangrove, were grouped into one (wetlands) as they have similar runoff response. After this, the slope categories and land use/cover maps were overlaid with standard GIS techniques. Also, based on the Nayarit soil chart (1:400 000), a map with the four categories (A,B,C,D) of Hydrologic Soil Groups (HSG), mostly related with the infiltration rates, was developed as recommended by the Natural Resource Conservation Service of USDA (USDA 1986). The intersection of this layer with the output from land cover and slopes was the basis for the assignment of the Curve Number and the final estimation of runoff by HRU.

Runoff estimation

Runoff was calculated for each HRU using the Natural Resource Conservation Service (NRCS) Curve Number method (USDA 1986). This is an empiric method that associates the HSG's, land cover, treatment, hydrologic conditions and antecedent runoff condition in a dimensionless parameter (USDA, 1986; Melesse y Shih, 2002), defined as:

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S}$$

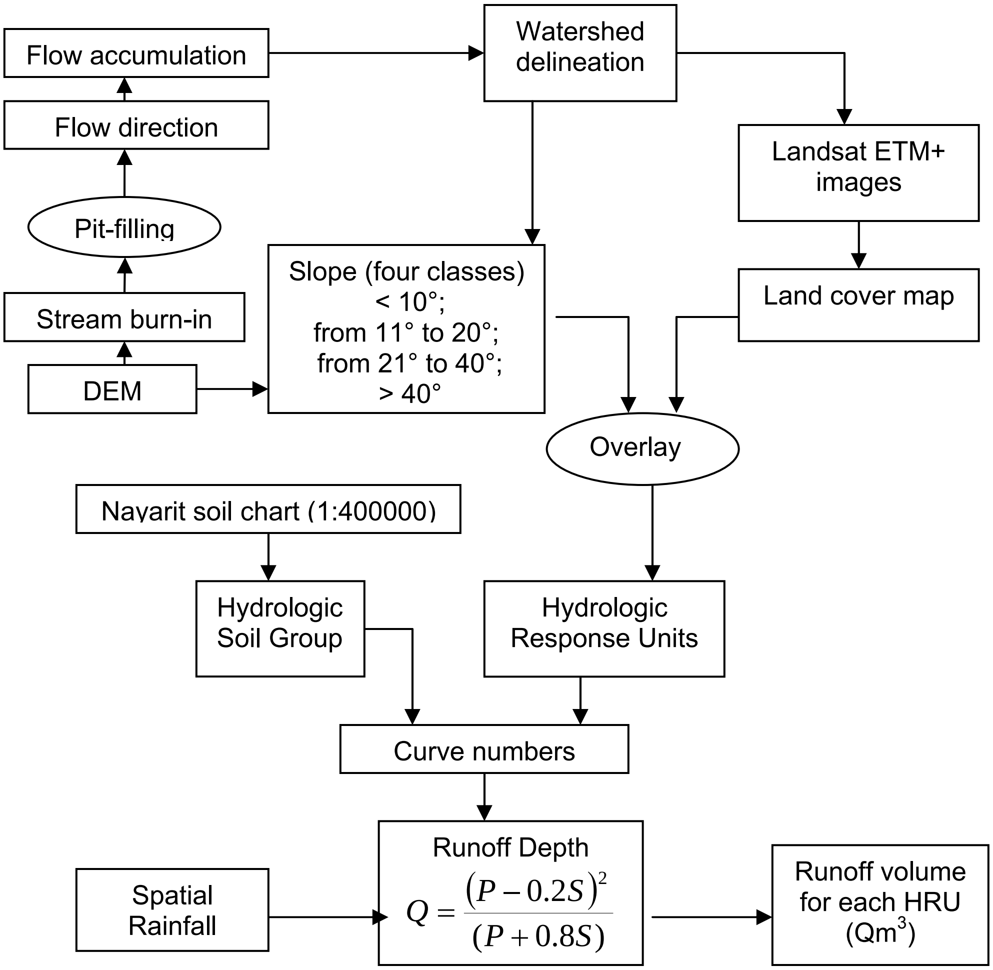
where *Q* is the runoff (mm), *P* is rainfall (mm), I_a is the initial abstraction that includes surface storage, interception and infiltration prior to runoff (mm), and *S* is the potential maximum retention after runoff begins (mm). As *S* and I_a can be empirically related ($I_a = 0.2S$) and S is a function of the soil moisture, then runoff can be estimated once the Curve Number (CN) is estimated (USDA 1986).

The CN varies non-linearly with the moisture content of the soil, dropping as the soil come close to the wilting point and increases to near 100 as the soil is close to saturation. To evaluate the runoff response for each HRU, both HRU and HSG map were overlaid and depending on the combination of attributes, a CN value was defined for each polygon and the outputs were processed with the ArcCN-Runoff tool developed by Zhan and Huang (2004) to estimate runoff depth (*Q*). The original model (USDA 1986) assigns a CN value of 0 for wetlands and aquatic systems, even when considering their saturated nature, some authors give them a CN value of 100. To be in agree with the used model, the CN = 0 value was assigned to those covers. In general, this procedure preserves details of the spatial variation and is more exact in the determination the curve number than direct calculation with data in raster format (Zhan and Huang 2004).

To assess the runoff response, an average rainfall event was considered for the sub-basin, as daily precipitation data exist for 11 meteorological stations from the Mexican Meteorological Service (SMN), located five of them in the limits of the sub-basin and the other close to it. Regarding this, it was not possible to have a detailed rainfall map and an average value for a typical storm was used. This value (P = 0.29”) was obtained from a precedent period of 10-year rainfall data. Finally, the runoff volume of each HRU was summarized to obtain the total runoff for the Rio San Pedro sub-basin. The whole procedure to delineate the HRUs and to estimate runoff is shown in Figure 3.

RESULTS AND DISCUSSION

Because the accuracy of DEM-derived drainage patterns is dependent on the accuracy of the source, the elevation values of the DEM must be accurate enough to capture the terrain features that influence drainage patterns (Jensen and Domingue 1988). In this study, a significant part of the study area is very flat, with altitudes lower than 1 m, and the vertical resolution of the used DEM's (1 m) is not sufficient to automatically extract the sub-basin boundaries.



$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

Figure 3. Delineation of HRU's and estimation of runoff volume

Regarding that stream network is the critical item in watershed delineation (Maidment 1996), additional efforts are required to assure a correct delimitation. Thus, in this study the stream burning technique allowed a better fitting of the DEM-based stream network with the reference hydrology map. The final delineation produced an irregular sub-basin shape, with a dendritic drainage pattern, formed from a series of first-order tributaries entering to larger streams at acute angles. The total area amounts around 2890 km^2, a very similar extent to that obtained by the National Institute for Statistics, Geography and Informatics (INEGI, Mexico), using manual methods on a surface hydrologic chart (scale 1:400 000), with differences lower than 1.0%.

The land use/land cover map associated with this area, including eight land cover classes, was produced with an overall accuracy of 82%, and User's and Producer's accuracies (UA and PA, respectively) of individual classes ranging from 59% to 100%. To avoid an overestimation of the accuracy, the classes Aquatic surface and Villages were excluded from the analysis due the particular spectral characteristics of the first class, whilst Villages class was digitized avoiding confusion with other classes. The analysis was done with 188 ground truth points for the six remaining classes.

The ^K coefficient was 0.78, that represents a substantial agreement between the classification output and the reference data (Landis and Koch 1977). Regarding this, the classification is better than one produced by the chance, and due the agreement level, was accepted as representative of the San Pedro sub-basin landscape.

From this, two thirds of the sub-basin were classified as Forest (191,600 ha), mainly distributed in the middle and north of the area and related to higher altitudes and irregular topography. Agriculture class is the second largest cover occupying about 11% (33,000 ha) of the study area and located in the middle of the sub-basin in areas with a slope range from 0 to 10 grades. In this order Exposed soils, Secondary succession, Mangrove, Aquatic surfaces, Saltmarsh and Villages occupy from 7% to less than 1% of the total area (Table 1). Mangrove cover, an important cover due the functions and services it offers to coastal ecosystems, was well discriminated from the rest of the classes (PA=93% and UA=97%), whilst Secondary succession and Exposed soils, strongly depending on agriculture activities, displayed low accuracies values (Table 1). This could have an effect on the runoff estimation, particularly where slopes are higher than 10º, but areas with these characteristics are less represented and do not imply a significant bias in the assessment.

Table 1. Estimated area (rounded to the nearest hundred) and proportion for eight land use/cover classes in the Rio San Pedro sub-basin, Nayarit, Mexico. User's and Producer's accuracies (%).

Land use	Area (ha)	Area (%)	User's accuracy	Producer's accuracy
Mangrove	10200	3.5	97	93
Saltmarsh	5600	2.1	86	90
Agriculture	33000	11.4	79	77
Secondary succession	19700	6.8	59	73
Forest	191600	66.4	79	89
Exposed soil	20700	7.2	100	66
Aquatic surface	5700	2.0		
Villages	1700	0.6		

Overall accuracy = 82%; Kappa (^K) = 0.78

With this in mind, 17 HRU's were integrated and delineated for the Rio San Pedro sub-basin, as a result of the simplification of the polygons initially obtained from the data layers overlay. They were ordered by runoff potential, which depends on the HSG – mean slope combination, starting with HSG-A (low runoff potential and high infiltration rates) and the lowest average slope. Because HRU represents a specific combination of slope, soil type, land cover and other characteristics, do not need necessarily to be contiguous and spatially related (Flügel 1995). The HRU's boundaries are shown in Figure 4 and some of their characteristics are displayed in Table 2.

This output shows that as consequence of the land use/cover distribution, all the forest -related units are the largest. The HRU 14 (Forest-Secondary succession) with mean slope of 30°, and the HRU 10 (Forest – mean slope 15°) are the best represented in the sub-basin, occupying around a half of the area. Because of their slope and the hydrologic soil type, with regosol as the most representative soil type, the CN associated is one of the highest (71), having these HRU's the maximum assessed runoff in the sub-basin. Then, to avoid an undesirable runoff increasing in this area, the forest must be preserved as it helps the water infiltration, considering that the HSG in this hydrologic unit is type C, which impedes downward movement of water and soils.

The highest CN value is for HRU 1 (Agriculture) even when the HSG (A) and low slope (4° in average), correspond to low runoff potential and high infiltration rates. Agriculture occupies slightly more than a tenth of the study area (32,732 ha), but it produces around 25% of the total runoff (Table 2). A similar condition is observed in the HRU 7 (Agriculture – villages) where the land cover change helps the runoff increasing and, together with the HRU 1 (Agriculture), has the highest runoff by area (138 m^3/ha and 196 m^3/ha, respectively), although the area represented by this HRU is small.

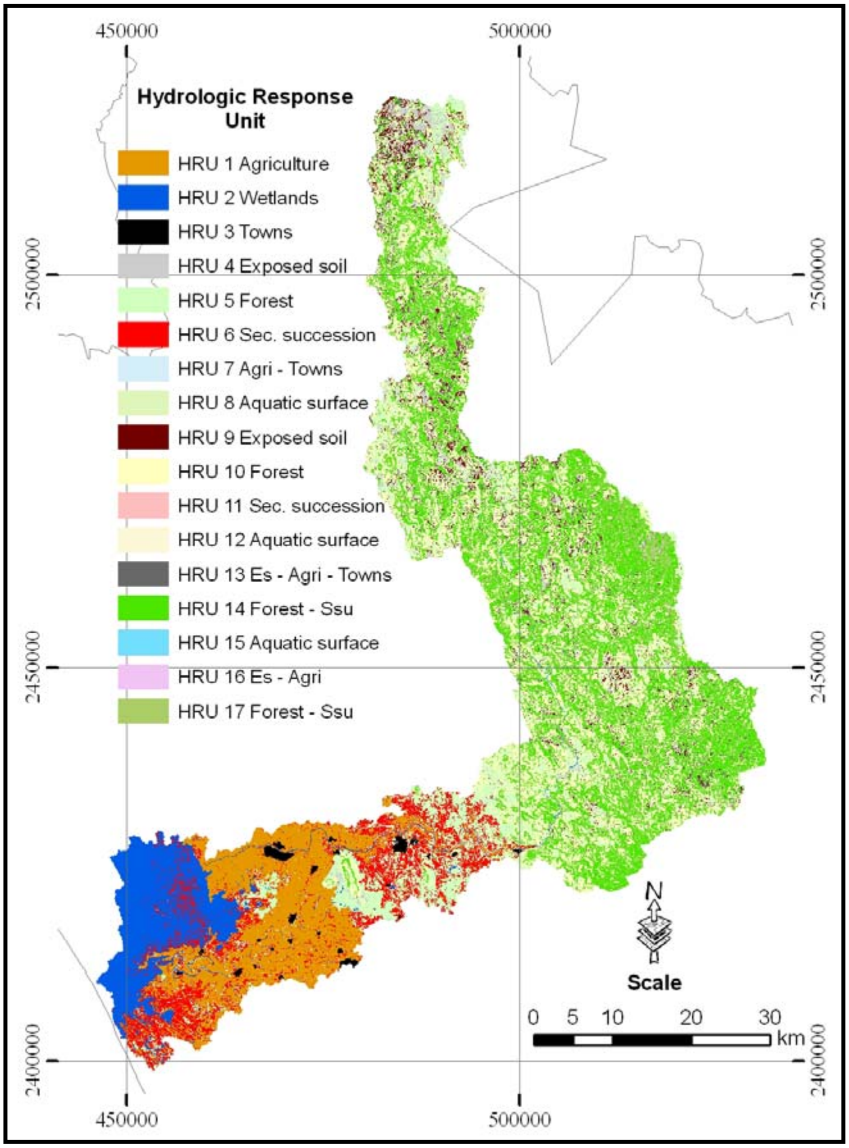


Figure 4. Hydrologic Response Units (HRU) map of the Rio San Pedro sub-basin, Nayarit, Mexico.

Table 2. Hydrologic Response Units of the Rio San Pedro sub-basin, Nayarit, Mexico. CN (Curve Number), Q (Runoff).

				Slope (grades)		Area			Q depth	Q	Q Vol/A
HRU	Land use	Soil type	HSG	Interval	Average	(ha)	%	CN	(mm)	(m^3)	(m^3/ha)
1	Agriculture	Fluvisol (89 %)	A	0 – 10	4	32700	11.4	84	21.7	4501280	138
2	Wetlands	Fluvisol (57%)	A	0 – 10	4	21600	7.5	0	0.00	0	0
3	Towns	Fluvisol (74%)	A	0 – 10	5	170	0.6	70	8.6	84938	50
4	Exposed soil	Cambisol (53%)	C	0 – 10	5	7500	2.6	72	9.5	776366	104
5	Forest	Cambisol (46%)	C	0 – 10	5	45000	15.6	70	9.0	3771920	84
6	Sec. succession	Cambisol (36%)	C	0 – 10	4	19300	6.7	55	3.6	845467	44
7	Agri-Towns	Cambisol (61%)	C	11 – 20	14	200	0.1	82	19.4	30374	196
8	Aquatic surface	Cambisol (54%)	C	11 – 20	15	200	0.1	0	0.00	0	0
9	Exposed soil	Cambisol (39%)	C	11 – 20	15	7700	2.7	72	9.6	843200	110
10	Forest	Regosol (43%)	C	11 – 20	15	63400	22.0	71	9.2	5954797	94
11	Sec. succession	Cambisol (81%)	C	11 – 20	15	400	0.2	52	2.1	25343	57
12	Aquatic surface	Regosol (47%)	C	21 – 40	30	100	0.03	0	0.0	0	0
13	Es-Agri-Towns	Regosol (45%)	C	21 – 40	29	4300	1.5	74	11.1	489142	113
14	Forest-Ssu	Regosol (48%)	C	21 – 40	30	77100	26.8	71	9.3	8136392	106
15	Aquatic surface	Leptosol (43%)	D	≥ 41	50	<50	0.00	0	0.0	0	0
16	Es -Agriculture	Leptosol (44%)	D	≥ 41	51	400	0.2	76	12.1	56759	129
17	Forest-Ssu	Leptosol (44%)	D	≥41	51	6600	2.3	75	11.2	861955	131
	Total					288119				26377933	

HRU 7. Agriculture and Towns
HRU 13. Exposed soil, Agriculture and Towns
HRU 14. Forest and Secondary succession
HRU 16. Exposed soil and Agriculture
HRU 17. Forest and Secondary succession

In this work, we adopted the total runoff assessment approach (Leavesley et al. 2002), instead the average approach (Sophocleous and Perkins 2000), regarding that HRU's are composed of distributed single areas which are summed up to a real classes (Bongartz 2003). This concept implies that topology of HRU subareas is very complex and the modeling of lateral flows cannot be conceptualized, which means that there is no connectivity between neighboring areas and no connectivity between areas and the river network. As a result all flows are integrated over the area and summed up at the catchments outlet.

Based on the results, there are three main HRU types in the Rio San Pedro sub-basin, which could be used for purposes of watershed management and runoff control. At first instance, the HRU's forest - high relief area related, unsuitable for traditional agriculture purposes (HRU 5, 10, 14, 17). Regarding the physical characteristics of these units, logging and deforestation could increase the runoff at risky levels for the lower areas. The second group includes units related with human activities, particularly agriculture and villages (HRU 1, 3, 7, 13, 16). Those areas are mostly low relief, located to the south of the sub-basin. Although they represent around 13% of the total area, contribute with one fifth of the total runoff, with high probabilities of escalating if the human activities increase on the URH's located in the lowland area, especially on the HRU's 4, 5 and 6, corresponding to exposed soil, forest and secondary succession.

Finally, a third group of HRU including wetlands and aquatic surfaces (river, estuaries and lagoons), is mostly located at the end of the sub-basin. This group does not contribute with runoff, but depends completely on the water supply and because of the economic and ecologic importance of services and goods that these environments provide, special considerations for the maintaining of these HRU's must be included in management plans for the watershed.

CONCLUSIONS

The analysis of a watershed following the HRU's approach seems to be quite effective for management targets, because the division of a wide area into small units, environmental physiographic or hydrologically analogous, facilitate and makes economic the development of management programs. In the present study the assessment of total runoff was achieved using this approach, retaining the spatial variability of the most important factors governing it. However, the output results are strongly dependent on the input quality, particularly in the drainage network and the current landscape patterns. Given that the delineation of the drainage structure agreed with the reference maps and that the landscape classification accuracy indices were between substantial and almost perfect concordance with the field data, we are confident that results represent a good approximation for the San Pedro sub-basin runoff assessment.

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