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ASSESSMENT OF LAND COVER CHANGE EFFECT ON THE HYDROLOGY OF THE SAN JUAN RIVER WATERSHED, NUEVO LEON, MEXICO

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This project evaluates the effect of potential land cover change on surface runoff generation in the San Juan River Watershed caused by population growth. A GIS based computer model, the Automated Geospatial Watershed Assessment Tool (AGWA), was used. Historical land cover type and river flow data available for the San Juan River watershed were used as model inputs and for model calibration, respectively. The computer model discretizes the watershed into six small units and predicts the watershed hydrology for future land cover conditions. Simulation results show minor changes in water flows at the watershed scale through the study period because subwatersheds that have land cover change make up only 23.5% of the study area. All the impact is concentrated in two subdivided regions (the urban areas and the Huajuco Canyon regions). In the urban areas, there is an increase up to 63.5% in surface flow when the area covered by the impervious surfaces grows 18.7% by 2020. For the Huajuco Canyon, there is a similar tendency. Flood hazard may increase due to increases in surface runoff during the wet season. There may be a local scarcity of surface water due to the dramatic decrease in percolation and baseflow during the dry season in the Huajuco Canyon and urban areas. The land cover change effect during an extreme rainfall event was evaluated using the rainfall event that occurred during Hurricane Gilbert in 1998. Simulation results show that land cover has a minimum influence on the volume of surface flow produced by this rainfall event.

INTRODUCTION

Environmental degradation in Mexico has become a nationwide concern. This problem may affect the governability and sustainability of the society. Problems such as soil degradation, deforestation, water resources degradation and loss of biodiversity are now considered as the origin of many social conflicts. Due to these conflicts, topics related to water resources and forest management are now considered national safety concerns (Cotler et al., 2004). Despite the development of natural hazard maps for Mexico at 1:250,000 scale, better maps need to be produced to assess flood hazards in a more reliable way. The production of such hazard maps will require watershed modeling similar to that described in this paper.

The San Juan River watershed has an area of 32,789 square km and is located in Nuevo Leon State and Coahuila state as shown in Figure 1. The main user of fresh water from the watershed is Monterrey, a major city located within this watershed. Monterrey currently has 3.5 million people, and is expected to increase to 5.1 million by year 2020. To meet the requirement of this population growth, around 25,000 hectares of land will become new urban areas in addition to the present 57,500 hectares (Guajardo, 2003). The growth of the urban areas will cause a change in land cover type from shrub or forest to impervious surfaces such as concrete or asphalt.

A significant correlation between watershed land cover type and hydrology has been described in several publications (e.g. Taniguchi, 1997). Land cover, especially forest, is one of the most influential factors in watershed hydrology. Forest cover increases percolation of water into the soil, which minimizes surface runoff and transforms potential surface runoff into groundwater preventing floods. Underground water travels slowly to springs and major streams, which prevents streams from being dry during the dry season of the year (Kostadinov et al., 1998). Significant increases in river flow resulting from conversion of forest land to agriculture was observed by several researchers (Heil et al. 2003; Williamson et al., 1987). Significant reduction of surface runoff followed by the growth of the vegetative land cover was demonstrated by Descheemaeker et al. (2006).

This paper presents a case study conducted at a watershed scale. The purpose of this project was to evaluate the effect of potential land cover change on watershed hydrology (percolation, surface runoff and stream baseflow). A GIS based computer model, the Automated Geospatial Watershed Assessment Tool (AGWA), was used. Historical land cover type and river flow data available for the San Juan River watershed were used as model inputs and for model calibration, respectively.

APPROACH AND METHODS

Description of the Study Area

The study area is a section of the San Juan River watershed in Mexico as shown in Figure 1. The San Juan River watershed is 6.35 % of the total drainage area of the Bravo River watershed. The extent of the study area is 3,488 km^2, which is all located in Nuevo Leon State. The average annual rainfall in the watershed is 414 mm (CNA, 2005). Fifty-seven percent of the watershed area has semi-hot weather with the average annual temperature between 18 and 22 degrees Celsius. The other part of the watershed (43% of the area) has hot semiarid weather, where the average annual temperature is above 22 degrees Celsius and the temperature of the coldest month is below 18 degrees Celsius. Water scarcity in the watershed is caused mainly by climate factors such as high levels of evaporation and low values of water vapor in the air due to high annual average temperatures. Also, since most of rainfall occurs between July and October when the temperatures are high, water is still scarce in the watershed despite the relative high total annual rainfall ranging from 600 to 1200 mm (INEGI, 1990). Dominant winds coming from the Gulf of Mexico (east) hit the mountains and most of the rainfall is concentrated in the east face of the mountain range (Figure 2).

The study area was divided into six regions including agriculture, forest, suburban, Huajuco Canyon, Huasteca Canyon, and urban areas according to the most prominent land cover type/use. Figure 3 shows the Landsat image of the study watershed obtained from Global Observatory for Ecosystem Services of Michigan State University (GOES, 1998).

The agriculture region, which is covered by grasslands and citrus farms, occupies 694 km^2 or 19.7% of the study area. Most of the region is flatlands except for some mountains in the west. The forest region covers 527.8 km^2 or 15% of the study area, all of which is mountains with heights of 3,000 meters above sea level. Although small areas are used for agriculture in this region, most of the area is covered by forest. The Huajuco Canyon region is south of Monterrey. It covers 370 km^2 or 10.5% of the study area and is undergoing rapid urbanization. Land cover in the mountain area is forests and in the valley area is shrub. New urban areas are mainly built in the valleys. The Huasteca Canyon region is isolated by the mountains, thus the rainfall is considerably lower than that in the other regions. It covers 1,145 km^2 or 33% of the study area, all of which is covered by mountains. Land cover in this largest region is scarce and is mainly desert shrub on steep slopes. The urban area is small compared to the total study area. It only covers 445 km^2 or 13% of the study area and is mainly Monterrey city. The land cover in this region is mainly concrete or asphalt with very small areas of terrain (parks or river channels). The suburban area covers 9% of the study area and its land cover is formed by low density urban and agriculture areas.

The GIS Based Model

The Automated Geospatial Watershed Assessment Tool (AGWA), a GIS based model, was used in this study (Miller et al., 2002). AGWA contains a Soil & Water Assessment Tool, the SWAT model (Arnold, 2000). The SWAT model is designed to predict the effects of land management practices such as agriculture, ranching, and urban development on watershed hydrology in large watersheds with different types of soils and for time periods greater than one year. It is a continuous time model that uses daily rainfall, soil, land cover type and terrain as input data. The SWAT model produces monthly and yearly results for percolation, surface runoff, baseflow and water yield for the modeled watershed in the output (Miller et al., 2002). It uses the Runoff Curve Number method developed by the Soil Conservation Service (SCS) of United States Department of Agriculture to estimate the surface runoff based on rainfall, soil and land cover type (USDA, 1986).

Rainfall and River Flow Data

Daily cumulative rainfall data from 1970 to 2000 was obtained from the Rapid Extractor of Climatological Information database. This database is based on the daily rain gage data obtained across Mexico (IMTA, 1999). The rainfall data used in this study was obtained from 20 weather stations installed in the study area (Figure 4). The continuous distribution of the daily rainfall data across the study watershed was obtained by applying the Thiessen polygons criteria using the point measurements from the rain gages (Miller et al., 2002). River flow records from 1970 to 1996 were obtained from the National Bank of Surface Water Data (IMTA a, 1999).

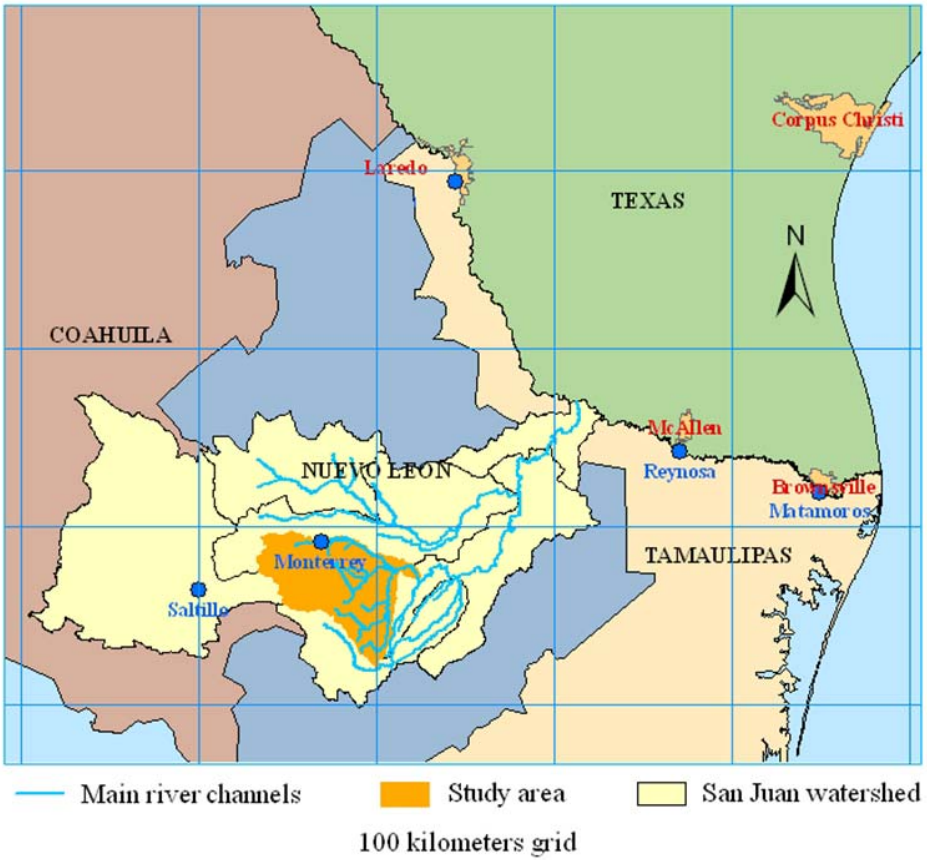

Figure 1. Study area within San Juan River watershed.

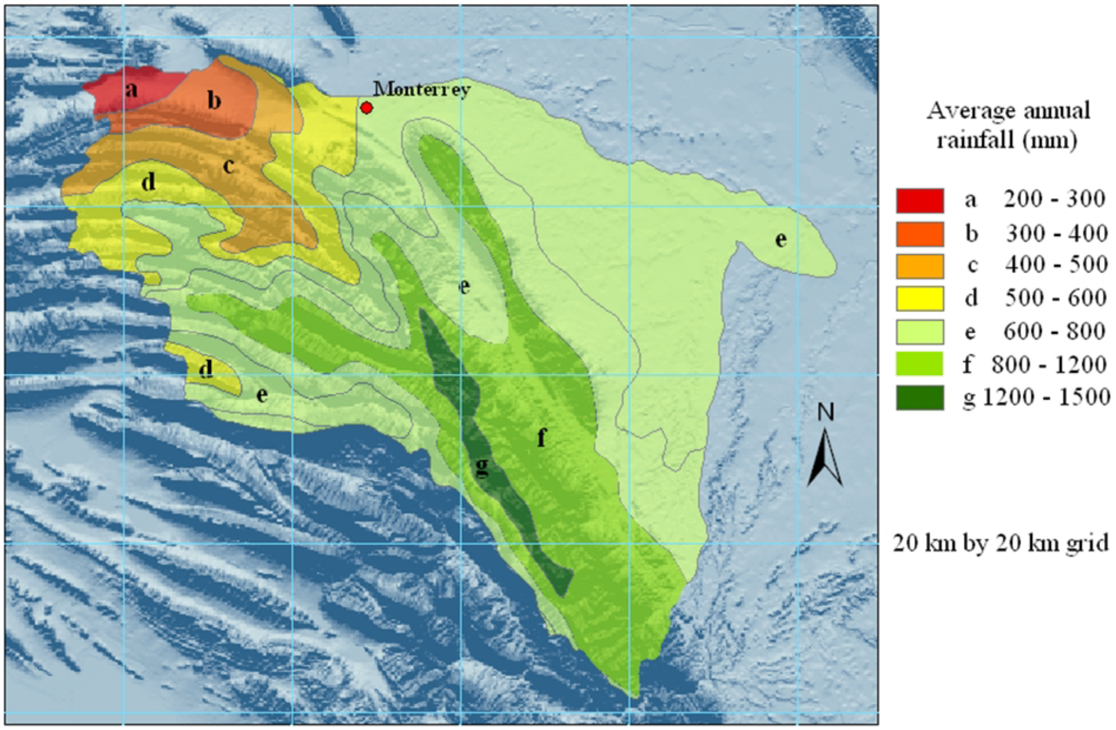

Figure 2. Distribution of rainfall in the study area.

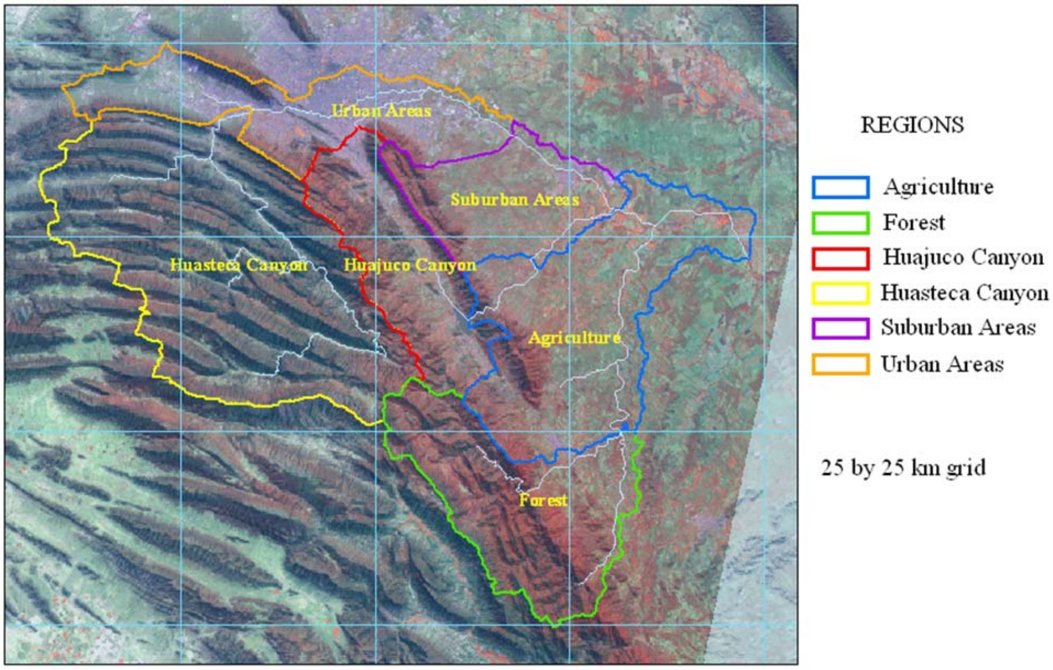

Figure 3. Landsat image of the study area and the division of the six study regions.

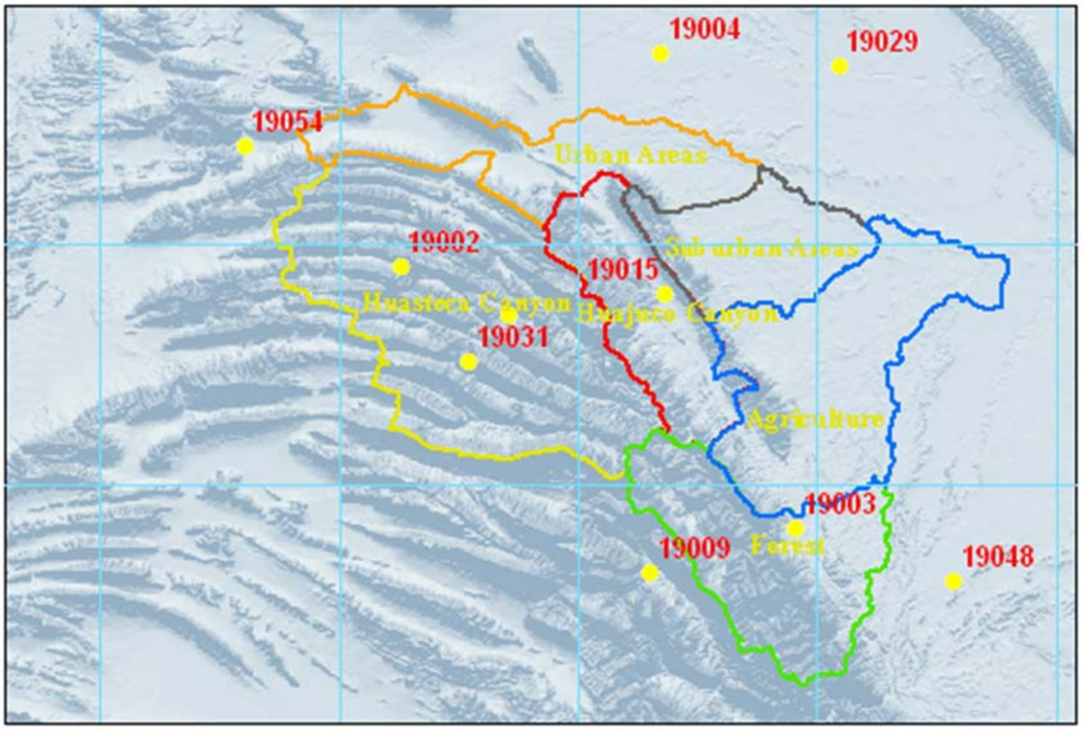

Figure 4. Location of weather stations used in this study, 30 km by 30 km grid.

Soil Data

Soil maps produced by INEGI (National Institute for Statistics, Geography and Informatics) (INEGI, 2000) using a 1:250,000 scale were used to classify soil data according to FAO (Food and Agriculture Organization of the United Nations) classification criteria (FAO, 1974). 182 different soil types were found in the study area according to the FAO classification. These FAO soil types were then reclassified into four hydrological soil groups, A, B, C or D following the work of Levick et al. (2002) and INEGI (2000). It should be noted that the relative large scale of the soil maps used can produce an error in the final simulation results due to the lack of detailed watershed soil data. In addition, Levick et al. (2002) worked on the reclassification from FAO criteria to USDA criteria. Since it is not a direct conversion, some simulation errors caused by this conversion are also expected. However, it is not possible to estimate these errors.

Land Cover Type

Mexico's land cover classification was developed by considering the features or the appearance of the vegetation (Moreno, 2002). Since this classification only provides details about land cover type but not the present use of the areas, this land cover classification was reclassified under the categories created by SCS (USDA, 1986). Land cover data for 2020 was estimated based on the results of the Strategical Analysis of Monterrey Metropolitan Area (Guajardo, 2003). In this analysis, the population is projected to grow 30% and urban area is expected to grow 40% from year 2000 to 2020.

Model Simulations

Before model calibration, the amount of surface runoff and baseflow was estimated using the records obtained from the gauge station at the exit of the watershed. The SWAT model baseflow program was applied to separate the baseflow from the surface runoff (Arnold, 1995). The daily river flow records obtained from 1970 to 1994 were used in this baseflow estimation. Six AGWA/SWAT model runs were conducted. The first model run was for model calibration and daily rainfall, river flow and land cover type data from year 1974 were used as model inputs. The model calibration was done by adjusting input parameters in the SWAT model as recommended in the manual (Neitsch et al., 2000). The second model run was for model verification and the land covers of years 1974 and 1998 were used as inputs to simulate the water flows in years 1976 and 1994, respectively. Model runs 3 through 5 were conducted to evaluate the effect of land cover change on watershed hydrology. Daily average rainfall from 1970 to 2000 and land cover data of 1974, 1998, and 2020 were used as inputs for model runs 3, 4, and 5, respectively. The sixth model run was conducted to assess the effect of land cover on the hydrological response of the study watershed area to an extreme rainfall event. The heavy rainfall event that occurred on September 17-18, 1988, during Hurricane Gilbert was used as model input (Murillo, 2002).

RESULTS

Hydrological Soil Groups

Figure 5 shows the resulting hydrological soil groups for the study area. 54.4% of the area is formed by type A soils, which consist of sands and gravels and have high percolation rates. Most of the type A soils are in the mountainous area. A type soils, with their high percolation rates, allow most of the water percolation in the watershed, thus they are very important for the rivers and their baseflow. Type D soils, consisting of fine texture clays and having the smallest capacity of absorbing water, cover 24.5% of the study area and are in flatlands. Type B and C soils, which consist of loam, cover 11.2 and 9.7 % of the study area respectively.

Land Cover Changes through the Study Period

Figure 6 shows the land cover datasets for years 1974, 1998 and 2020. The percent contribution of each land cover type to the total area was calculated and results are shown in Figure 7. From 1974

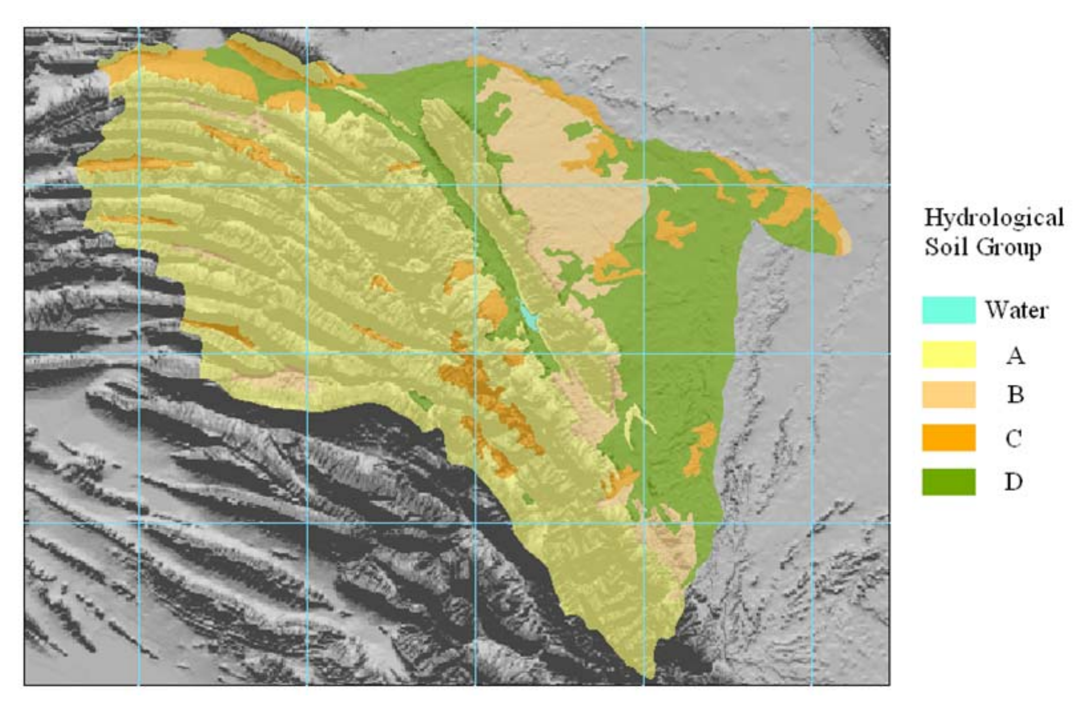

Figure 5. Hydrological soil types in the study area, 20 km by 20 km grid.

to 1998, there was a 5.1% decrease in desert shrub cover in the study area. In 1974, only 2.2% of the watershed was covered by urban areas. By 1998 urban areas covered 6.8% of the area, and they are projected to cover 10.9% of the area by 2020. The most notable changes are the shrinking of the shrub areas, and the growth of the urban areas. The growth of the urban area is further shown in Figure 8, where yellow areas (grasslands, desert shrub or agriculture areas) in 1998 will likely be converted into urban areas by 2020. Green areas were desert shrub and agriculture areas in 1998 and will be transformed into forest areas in 2020. The area converted into urban areas in 2020 is 18.7% of the original urban areas region. For Huajuco Canyon, 19.7% of the total area of the region will be converted from grassland and desert shrub to the urban area in 2020.

Rainfall Variation

Daily rainfall data is available from 1970 to 2000 for all weather stations. Monthly rainfall data for the years closer to the date of release of land cover type data used in the study are shown in Figure 9. The month with the highest precipitation occurred in September for 1974, July for 1975, August for 1998, and October for 1999. The average annual rainfall is 463 mm for 1974, 683 mm for 1975, 489 mm for 1998, and 632 mm for 1999. Because of the variations in rainfall amounts among different years, a runoff simulation conducted using year 1974 rainfall can not be compared with a runoff simulation conducted using 1998 rainfall. To prevent the interference of rainfall variations in the comparison of land cover effect, the average daily precipitation from 1970 to 2000 was used as the input for all of the model runs.

SWAT Model Calibration and Verification for Surface Runoff

The baseflow and surface runoff estimated using the SWAT model baseflow program were 39.5% and 60.5% of the total river flow, respectively. Figure 10A shows the model calibration results for monthly surface flow for year 1974. The input parameters used for the final model calibration are the available soil water capacity of 0.28, soil evaporation compensation factor of 0.65, 1020 mm of the threshold depth of water in the shallow aquifer for evaporation to occur, and

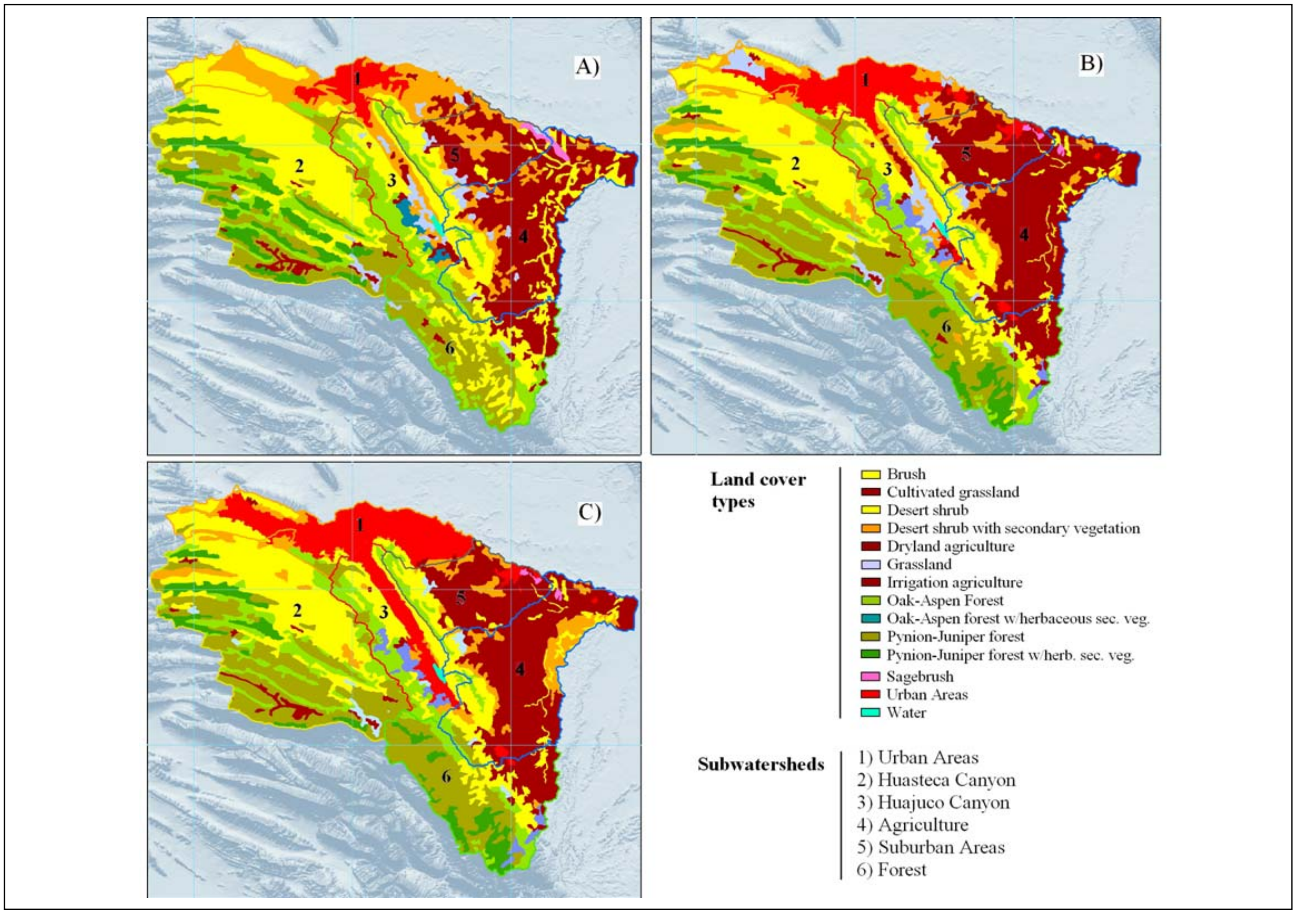

Figure 6. Land cover types for A) year 1974, B) year 1998, and C) year 2020. 25 km by 25 km grid.

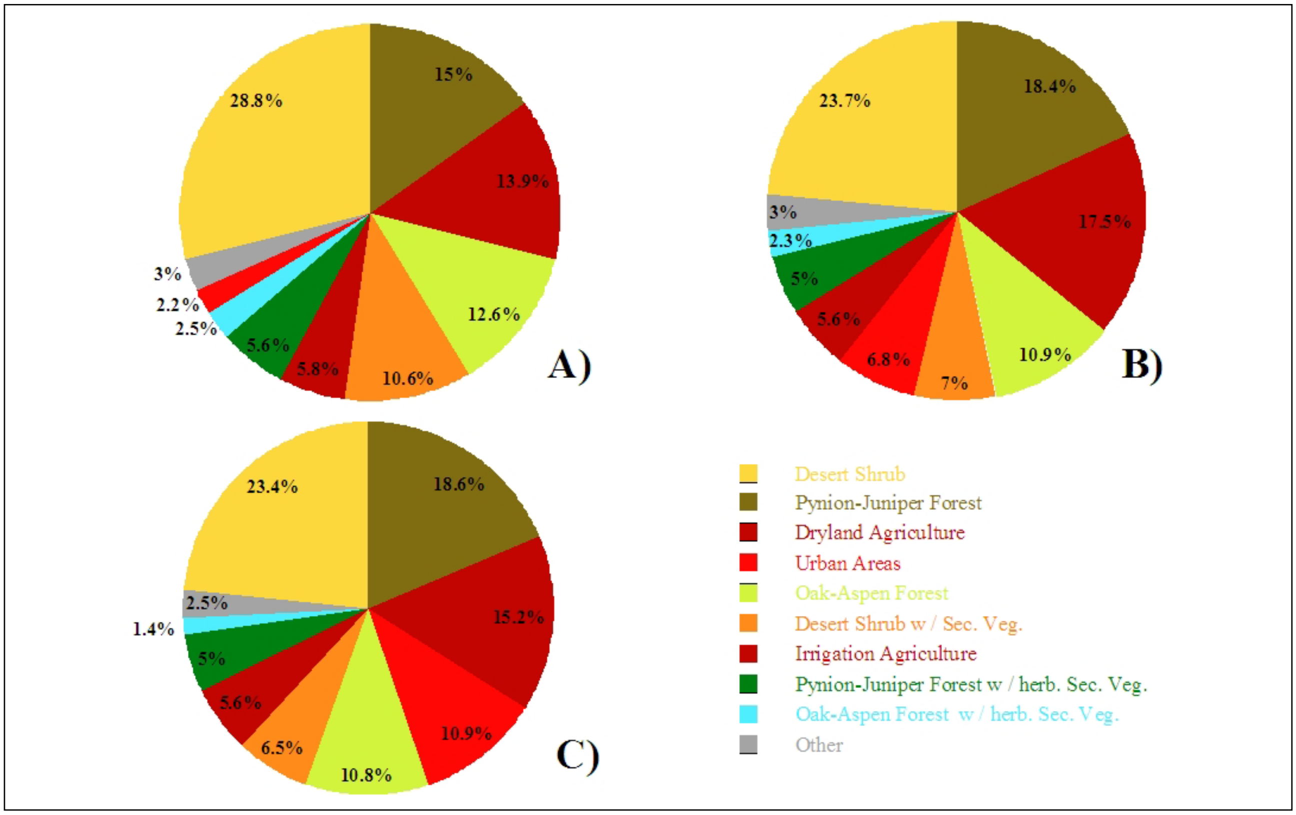

Figure 7. Percent contributions of each land cover type to the total area for A) year 1974, B) year 1998, and C) year 2020.

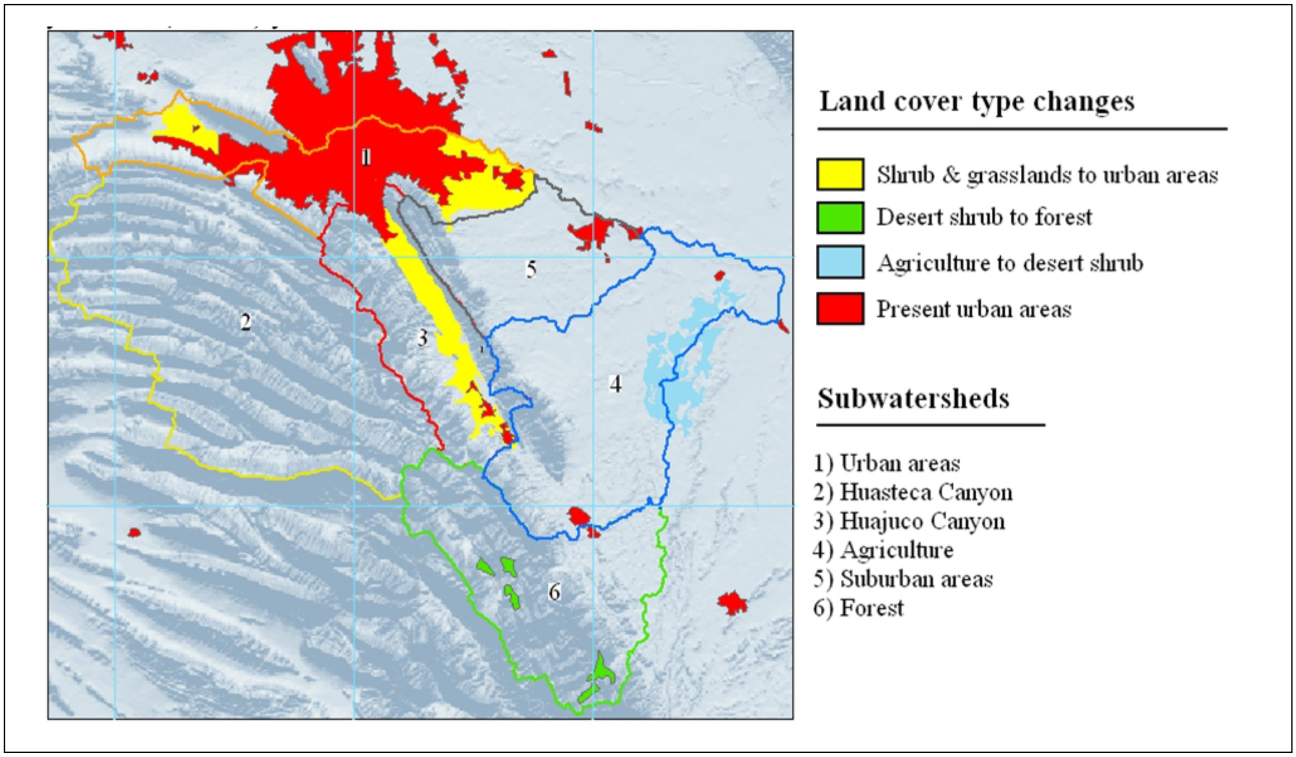

Figure 8. Major changes in land cover from year 1998 to year 2020.

the baseflow recession constant of 0.0313. The percent difference between the simulated and the measured flows was calculated and the results are shown in Figure 10A. The percent difference ranged from -3.9 percent to 39.3 percent during months of the rainy season (September, October and November) and ranged from -148 percent to 11.8 percent during the dry season of the year. The percent difference for the annual accumulated flow is 1.5%. The model verification results are shown in Figures 10B and 10C respectively. The percent difference between the simulated and measured flow values for the year-round accumulated flow is 2.1% for 1986 and 6.8% for 1994. The percent difference for the monthly river flows is up to 27.8% for 1986 and 41.7% for 1994 during the rainy season (September, October and November). Since 85% of the accumulated yearly flow in the river occurred during the rainy season, the evaluation of the model calibration and verification results should focus on the rainy season. Thus, the above percentage errors are considered acceptable for assessment purposes in this study.

Simulated Annual Average Flow

Figure 11A shows the simulated annual average flow for the entire study area. The land cover changes cause 0.7% and 4.2% increase in surface runoff and 5.0% and 6.7% decrease in baseflow in 1998 and 2020 respectively. However, the overall water yield (the sum of the surface runoff and the baseflow) at the watershed outlet drops 2.4% and 1.8% in 1988 and 2020 respectively, despite the land cover changes in the urban areas and Huajuco Canyon regions as presented above.

Figure 11B shows the simulated surface runoff changes for the six regions in the watershed. The biggest increase in surface runoff between 1974 and 2020 is found in the urban areas and Huajuco Canyon regions. Recall that urban areas increased by 18.7 percent from 1974 to 2020. However, this change in the urban areas causes a 63.5% increase in surface runoff in 2020 in this region. For Huajuco Canyon, although only 19.7% of the total area of the region was converted from grassland and desert shrub to the urban area, this change causes an increase in surface flow of 17.8% by 2020.

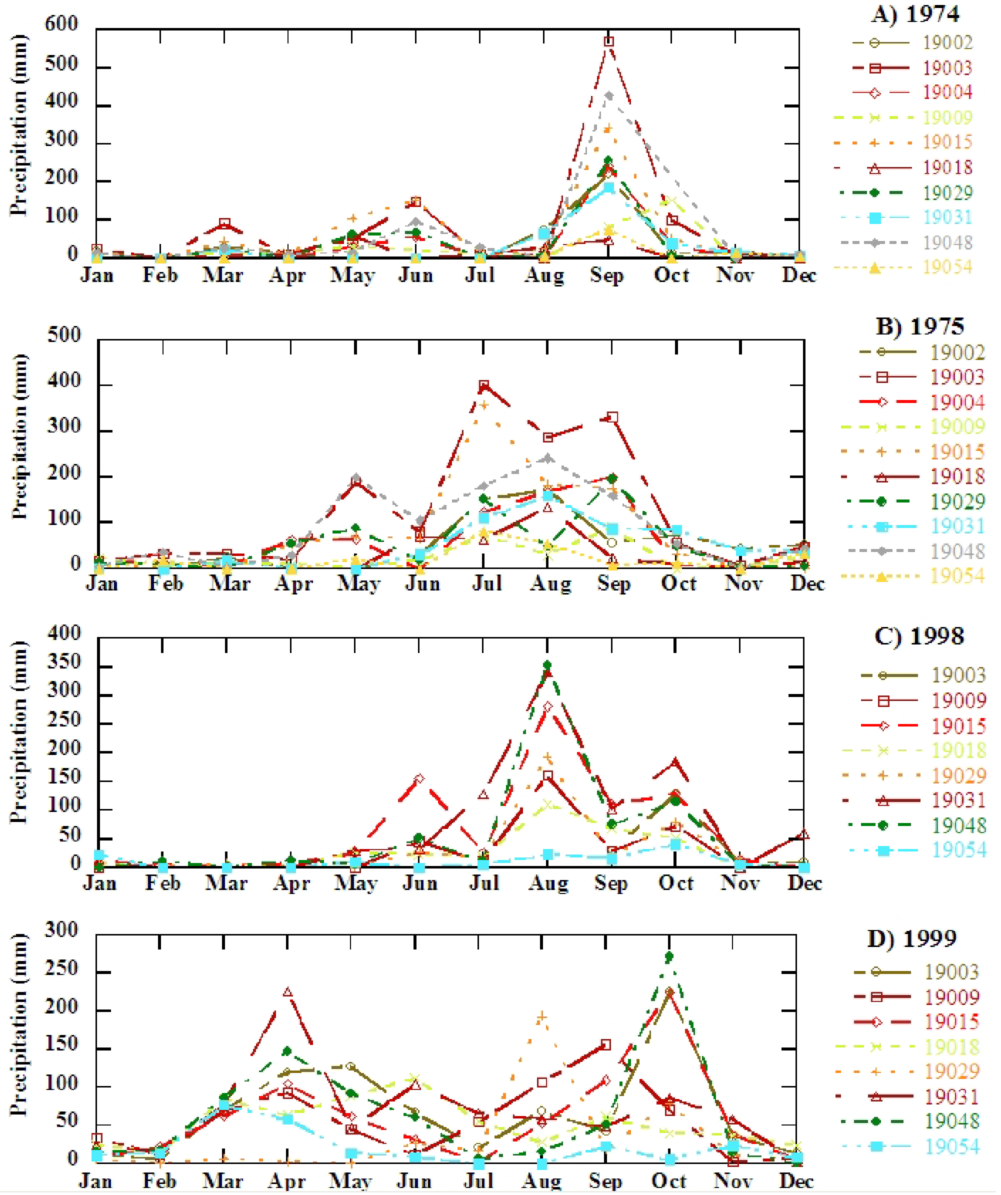

Figure 9. Monthly rainfall data collected at different weather stations in the study watershed in years A) 1974, B) 1975, C) 1998, and D) 1999.

A comparison of detailed percolation changes among the six regions is shown in Figure 11C. The biggest drops in percolation are found in Huajuco Canyon (10.4%) and urban areas (66.4%) for 2020. Reduction of percolation results in more water leaving the watershed as surface runoff in Huajuco Canyon and urban areas. In the forest region, increased percolation (5.2%) causes a decrease (15.4%) in surface runoff in 2020.

Figure 11D shows the simulated volume of annual baseflow. The largest differences of annual baseflow between 1974 and 2020 are found in the urban (-54.7%) and agriculture (-9.1%) regions. This is because grasslands and desert shrub were converted into urban areas (the land cover types that reduce the percolation) in the urban areas region, and agriculture areas are expected to be abandoned and return to desert shrub cover type in agriculture region by 2020 as shown in Figure 8.

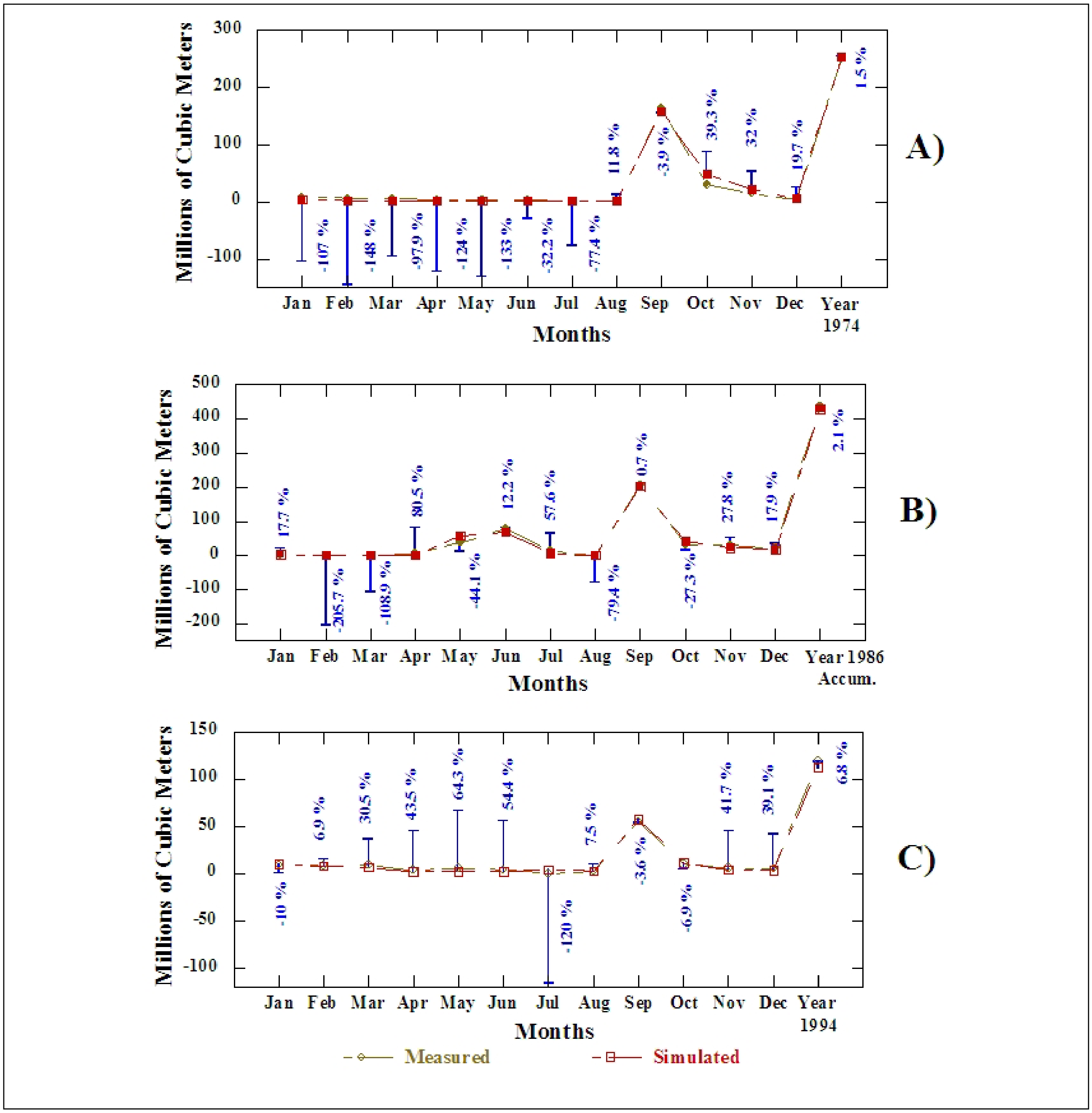

Figure 10. A) SWAT model calibration results for monthly surface flow and annual accumulated flow for year 1974, B) Model verification results for monthly surface flow and annual accumulated flow for year 1986, and C) Model verification results for monthly surface flow and annual accumulated flow for year 1994. Blue bars and values indicate the percent difference between the simulated and measured flows.

Watershed Hydrological Response to an Extreme Rainfall Event

Figure 12A shows the simulated water flows for the entire study area. Similar to the results shown in Figure 11A, the total volumes of surface flow and baseflow, the water yield, only show small changes from 1974 to 1998 (1.0%) and 2020 (1.9%) respectively. However, surface flow is 10 times greater than baseflow in September 1988 during the extreme rainfall event. The surface runoff simulated using this extreme rainfall event has a small increase (3.1%) from 1974 to 2020 in consideration of the land cover changes. The changes in baseflow and percolation are also small from 1974 to 1998 and 2020.

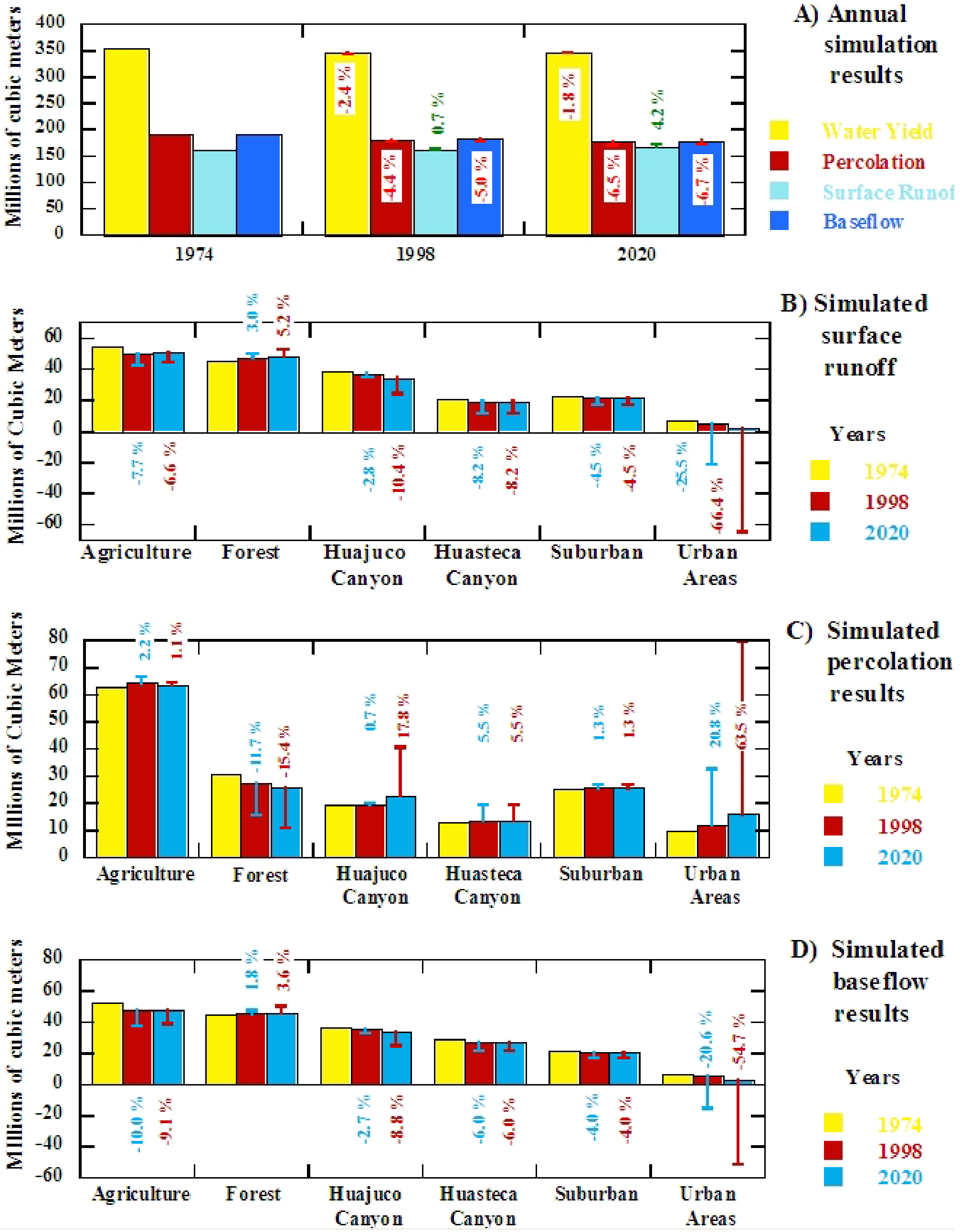

Figure 11. A) Simulated annual flow data and percent changes in years 1998 and 2020 compared with that in year 1974 for the whole study area, B) simulated annual average surface flow and percent changes in years 1998 and 2020 compared with that in year 1974 for the six regions, C) simulated annual average percolation and percent changes in years 1998 and 2020 compared with that in year 1974 for the six regions, and D) simulated volume of annual baseflow and percent changes in years 1998 and 2020 compared with that in year 1974 for the six regions.

Figure 12B shows the simulated surface flow for each region using the rainfall event that occurred in September 1988 during Hurricane Gilbert. There is 7.5% decrease in the forest region and 5.5% increase in the urban areas in surface flows between the simulated years. Compared with Figure 11B, changes in surface flow are smaller, which indicates a smaller effect of land cover on surface flow in the case of this extreme rainfall event.

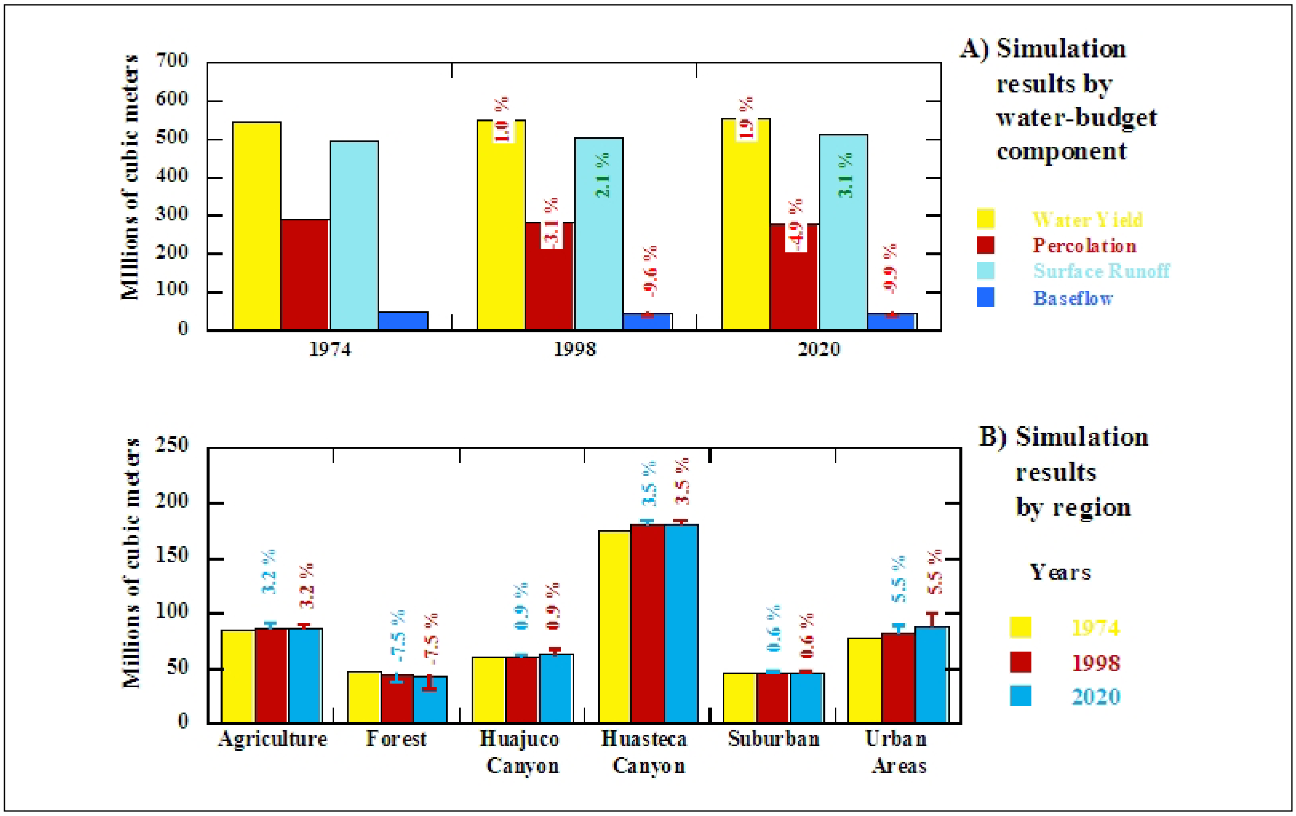

Figure 12. A)Simulated water flows and percent changes for the entire study area. The percent changes are changes of flow in year 1998 and year 2020 compared with that in year 1974. And B) Simulated surface flow and percent changes for the six regions. The columns show the absolute flow values in millions of cubic meters. The blue bars and labels show the percent difference between year 1974 and 1998 flow values. The brown bars and labels show the percent difference between year 1974 and 2020 flow values.

DISCUSSION AND CONCLUSIONS

Soil and land cover data available in Mexico was successfully adapted to serve as input for SWAT model. Rainfall information was sufficient although data for a few days were missing in rainfall records over a 30-year study period. Results of SWAT model calibration and verification were as expected, which allowed the SWAT model to be used in simulating and assessing the effect of land cover changes on the watershed hydrology in the study area.

Simulation results show that surface runoff increased considerably in the urban areas and the Huajuco Canyon regions, as a result of projected land cover transformation from shrub and grasslands to urban areas from 1974 to 1998 and 2020. The increase of surface runoff for the urban areas region is up to 63.5% when the area of the subwatershed covered by impervious surfaces grows 18.7%. For the Huajuco Canyon region, an increase of 19.7% in the area covered by urban areas causes an increase of 17.8% in the surface flow in year 2020. This increase in the surface runoff shows a possibility of increase in occurrence of floods in wet season. Results show a tendency towards decreasing baseflow over time in the Huajuco Canyon and urban areas regions. This decrease may lead to a reduction in the flow volume in perennial surface streams, which may result in a local scarcity of surface water in dry seasons.

Despite the simulated flow, land cover changes, and potential water resources problems in urban areas and Huajuco Canyon regions, the water yield for the entire study watershed area remains almost unaltered (a decrease of 2.4% in 1998 and 1.8% in 2020, which are not significant when uncertainties in watershed computer modeling are considered). This is mainly because these two subwatersheds cover only 23.5% of the entire study area. The unaltered land cover in the Huasteca Canyon and forest region serve as a "buffer" to absorb the impacts of urbanization in other regions of the watershed. Particularly, the A type soils in these regions reduce runoff from rainfall due to their high percolation capacity. As a result, the percolation of the soils in these regions is actually independent from any land cover change, although land cover effect on percolation is considered. Thus, the water availability in the entire watershed may not be compromised in the near future.

In the case of the hurricane rainfall event, simulation results indicate that the effect of land cover type on water flow volume produced by extreme rainfall in the watershed is negligible. This can be attributed to the significantly higher surface flow compared with the base flow caused by the limited soil percolation capacity.

The results must be analyzed very carefully since the SWAT model only generates volumes of water flow in the output, which does not indicate how much time it takes for the water to reach the watershed outlet. Flooding depends on two factors: the accumulated rainfall and the concentration time. Accumulated rainfall determines how much water is available in the watershed. The concentration time is affected directly by land cover type because land cover type determines how fast the water leaves the watershed. Land cover aggregates rugosity to soil, thus water takes more time to get to the outlet in a watershed with a dense vegetative land cover (Singh, 1992). The magnitude of a flood can not be estimated using SWAT model alone. Other hydrological models, which can simulate the concentration time, need to be used to more accurately assess the flooding process in future studies.

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