Changes in land use cover and its effects on hydrometeorological risk in Tuxtla Gutiérrez (Mexico)

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Abstract. To better understand the space-time dynamics and the effect of urban growth on the transformation of territory, this article presents the results of Iber 2D simulation tests to analyze flood events in the lower Sabinal river basin, Tuxtla Gutiérrez, Chiapas, Mexico. First, Landsat 5 and Landsat 8 satellite images from 1986 and 2014 years were processed to generate classified images of the land cover of the study area. From the identified coverages, the soil roughness values were defined, as well as the infiltration parameter of water in the soil. Both values were used as input data in an Iber 2D simulation model to analyze and compare the maximum flood level with different precipitation values in the two reference years. Between 1986 and 2014, the coverage of urbanizations increased considerably, while the coverage of trees, pastures and agriculture decreased. Due to this change in coverages, in 2014 rainfall caused higher values of direct runoff, increasing water heights and therefore the risk of overflowing the Sabinal River. With the model shown here, it is possible to calculate the depth and water heights reached and identify the points and moments of overflow of the river. This model can be used to provide feedback to flood risk warning systems and to analyze basins that lack monitoring infrastructure.

1. Introduction
Flooding due to extreme hydrometeorological events has become a recurrent problem in the world's tropical and subtropical regions [1]. Much of these floods are magnified by land use change [2, 3]. In urban areas, floods tend to be more severe, causing loss of life and damage to property and infrastructure [4].

For proper management and prevention of hydrometeorological risks, it is necessary to map current and potential land coverages, in addition to identifying main and secondary river channels and delimiting flood areas, among other actions [5-7]. Modern remote sensing technologies and Geographical Information Systems (GIS) are very useful for characterizing the territory and conducting temporal analyses showing the evolution and changes in land cover and land use [8, 9, 4, 7]. Hydrometeorological models, on the other hand, make it possible to analyze the effect of rainfall on surface runoff, delay time, depth and water heights, among other factors, at different scales in the river basin [8, 10]. There are different calculation methods and software that greatly facilitate hydraulic or hydrological modeling. Some of these tools that have been used in Latin America are: Hec-Ras [11, 12], Hec-Hms [13], 2D Infoworks [14, 1, 15, 5] and the permanent flow simulation...
program of the UNAM Engineering Institute [16]. In the Latinoamerica context, recently the possibilities of the Iber 2D model have been explored, for the two-dimensional hydraulic simulation [17].

In its intermediate versions, Iber includes a hydrological module that allows, with a good level of precision, to represent the rain–runoff processes [18, 19]. Using its hydrological variables and routines, Iber can be used to predict river overflows based on certain precipitation levels and terrain characteristics [20].

In this article we analyze the results of simulation tests with Iber, 45, 60 and 98 mm/h of rain which were applied in a polygon of the urban area of Tuxtla Gutiérrez, using detailed information of its topography and land cover. These simulations were applied in order to address the following main objective: to analyze how changes in land cover of the Sabinal river basin have affected the values of surface runoff and water depth in the main channel.

2. Methods and Materials

2.1. Study area
The Sabinal River Basin, with a total surface of 407 km² is located in Tuxtla Gutiérrez, Chiapas, Mexico. It has an altitude ranging between 379 and 1200 m, average annual temperatures between 20 and 28 ºC and average annual rainfall between 900 and 2000 mm [21]. The specific study area, where simulation tests were applied, corresponds to a polygon of 60 km² in the lower part of the Sabinal River Basin, where all the streams of the basin drain. This polygon is located in the urban and densely populated area of Tuxtla Gutiérrez, from an elevation of 615 m west of the city to an elevation of 379 m, where it flows into the Grijalva River (figure 1).

![Figure 1. Study area based on data from INEGI [25] and SHGEC [21].](image-url)
2.2. Hydrometeorological Alert System of Tuxtla Gutiérrez

In order to monitor rainfall and flow generated in the Sabinal Basin, the Hydrometeorological Alert System of Tuxtla Gutiérrez (SAHT) was installed with rainfall stations distributed in the middle and upper parts of the basin, and level stations to record the depth of water in the main riverbed as it passes under several vehicular bridges [22-24].

Based on the historic height records of the riverbed, the National Water Commission (CONAGUA) [23] established three levels of depth in each level station, which allow monitoring and, if necessary, alerting the population about the risk of the river overflowing. These levels are: a) the minimum level corresponds to the river bed, b) the critical level (approximately 60% of depth) indicates that there is a high risk of the river overflowing, and c) the maximum level (100% of depth) in which the river definition is lost due to the flooding [22, 23] (table 1).

This article compares the minimum, critical and maximum levels obtained through simulation tests in five selected level stations, which are homogeneously distributed along the main riverbed, and correspond to points where river overflows have occurred [22, 23].

Table 1. Level Stations of the Tuxtla Gutiérrez Hydrometeorological Alert System.

| Level station          | Minimal | Critical | Maximum |
|------------------------|---------|----------|---------|
| Terán-Aeropuerto       | 557.60  | 561.00   | 561.70  |
| Parque Joyyó Mayu      | 541.50  | 544.70   | 546.00  |
| Centro 2a. Poniente    | 514.80  | 518.10   | 519.20  |
| Puente IMSS            | 506.27  | 509.50   | 511.50  |
| Parque Oriente         | 493.20  | 497.00   | 499.00  |

Minimal: height of the river bed.  
Critical: 60% of the water height; there is a high risk of the river overflowing del río.  
Maximum: 100% of the water height; the height where the river definition is lost due to the flooding.  
Source: Adapted from CONAGUA [23, 24]

2.3. Analysis of changes in land cover and land use

The ground cover of the study area was obtained by means of supervised classification of Landsat images (30x30 m optical bands), one from 1986 (Landsat 5 Thematic Mapper (TM)) and another from 2014 (Landsat 8 Operational Land Imager (OLI)). Coverages of 1) trees, 2) agriculture (pastures and crop fields), 3) bare soil and 4) residential use (urbanizations and infrastructures) were identified and quantified. A confusion matrix was prepared, obtaining an overall reliability of 80 and 85% in the 1986 and 2014 classifications, respectively. Based on this, coverage A in 1986 and coverage B in 2014 were obtained (table 2). The information obtained on land cover was used to define distributed soil roughness values ("n" manning coefficient), assuming the ranges proposed by Martinez and Fernandez [24]. Likewise, in order to calculate surface runoff, an aggregate loss index of the study area was obtained, weighting the values corresponding to each type of coverage, obtained from the curve number tables [10] (table 3).
**Figure 2.** Flood analysis: simulation process with Iber, from a Lidar DTM and classified Landsat images.

**Table 2.** Land cover obtained from Landsat image classification (km²).

| Coverture     | 1986 | 2014 | Δ 1986 - 2014 |
|---------------|------|------|---------------|
| Trees         | 5.95 | 7.18 | 1.23          |
| Agricultura   | 40.38| 21.40| -18.98        |
| Residential   | 13.65| 30.08| 16.43         |
| Bare ground   | 0.34 | 1.66 | 1.32          |
| **Total**     | 60.31| 60.31|               |

Source: Prepared by the authors, based on the classification of Landsat images.
Table 3. Values assigned in the pre-processing stage, in simulation tests with Iber.

| Land cover types      | Coverture A: 1986 | Coverture B: 2014 | Roughness (Manning) |
|-----------------------|-------------------|-------------------|---------------------|
| Trees                 | 10%               | 12%               | 0.12                |
| Agricultural          | 67%               | 35%               | 0.04                |
| Bare ground           | 1%                | 3%                | 0.15                |
| Residential           | 23%               | 50%               | 0.023               |
| "Losses" NC          | 85                | 89                |                     |

a/ The proportions correspond only to the portion of the land delimited by the DTM, and are the result of the supervised classification of Landsat images.
b/ The roughness values proposed by Martínez and Fernández [24] were adopted.
c/ Weighted value of NC, based on proportions of land cover.
d/ Precipitation values were estimated for the indicated return times (tr) from the data series in table 4.

2.4. Water depth simulation with Iber
Firstly, a digital terrain model (DTM) was generated from LIDAR (Light Detection And Ranging) data, with pixels of 5x5 m and height in centimetres, provided by the National Institute of Geography, Statistics and Informatics [26], corresponding to a 2007 flight. Subsequently, on an unstructured triangular mesh generated from the DTM, simulation tests were carried out with Iber version 2.3.4 software to observe the effect of rainfall as a function of land cover, both for 1986 and for 2014 (figure 2).

A total of six simulation tests were performed as a result of the combination of the two coverage areas (Coverage A: 1986; Coverage B: 2014) and three precipitation levels (1: 45; 2: 60; and 3: 98 mm/h).

Just that is, each of the cover layers was assigned, first, a strong precipitation of 45 mm/h (p45), which in theory does not exceed the capacity of the main Sabinal channel (Tests A1 and B1); later, a very strong precipitation of 60 mm/h (p60), which can cause overflowing in some points of the river (Tests A2 and B2); and, finally, an intense rainfall of 98 mm/h (p98) which causes the river to overflow at several points (Tests A3 and B3), according to CONAGUA [23].

The value of 98 mm/h corresponds to a maximum precipitation in 24 hours (P_{max24}), for a return period of 10 years (TR10); 60 mm/h and 45 mm/h correspond to return periods of 1.4 and 1 year, respectively. These values were calculated by the Gumbel method [10] from the data in table 3, corresponding to maximum values of annual precipitation of 24 hours in Tuxtla Gutiérrez pluviometric station nº 7202, provided by SMN, for the period 1988-2016 [27].
Table 4. Maximum annual rainfall of 24 hours, hydrometeorological station 7202, Tuxtla Gutiérrez Chiapas

| year | P(max) | year | P(max) | year | P(max) | year | P(max) |
|------|--------|------|--------|------|--------|------|--------|
| 1988 | 66.3   | 1996 | 71.5   | 2003 | 85.3   | 2010 | 104.7  |
| 1989 | 87.2   | 1997 | 48.7   | 2004 | 92.3   | 2011 | 89.7   |
| 1990 | 63.2   | 1998 | 61.3   | 2005 | 50.0   | 2012 | 80.0   |
| 1991 | 81.5   | 1999 | 54.1   | 2006 | 63.0   | 2013 | 63.1   |
| 1992 | 39.8   | 2000 | 52.5   | 2007 | 78.0   | 2014 | 76.9   |
| 1993 | 82.0   | 2001 | 52.3   | 2008 | 71.1   | 2015 | 95.0   |
| 1994 | 72.0   | 2002 | 77.9   | 2009 | 58.0   | 2016 | 108.5  |
| 1995 | 77.7   |      |        |      |        |      |        |

Source: Prepared by the authors, with data from [27].

In the pre-processing stage with Iber, on the simulation mesh, the soil cover was assigned (A: 1986; B: 2014) the weighted value of losses (NC) and discretised values of soil roughness. As an independent variable, an intensity histogram was assigned that emulates a precipitation of 2.5 hours (with p1 = 45; p2 = 60; or p3 = 98 mm/h) (table 3). The flow outlet was located just where the Sabinal flows into the river Grijalba. The simulation period was set at 20 h, with time steps of 5 min.

In the post-processing stage with Iber, by means of the corresponding coordinates, the triangle elements corresponding to the five selected SAHT stations were identified in the simulation mesh. These elements are called registration points and are identified with the following abbreviations: TA, PJM, C2P, IB, PO (table 7).

From Iber's results files, the maximum water depth (dependent variable) values corresponding to each of the recording points were recovered (table 7).

2.5. Validation of the model of simulation

With respect to hydrometeorological variables, although there are complete historical series of rainfall recorded at rainfall stations located in the Sabinal River Basin, there is no consistent record of hydrometric variables. Therefore, SMN precipitation data cannot be directly correlated with CONAGUA reported water flow and depth values.

In order to validate the results of the simulation model, the total runoff generated by p45, p60 and p98 on 2014 coverage (B coverage) was calculated using the curve number method (NC) (Table 5). This runoff was then compared with the total runoff values obtained by simulation tests with Iber. Both results were contrasted using the Nash-Sutcliffe index (table 6).

2.5.1. Estimation of total runoff using test of simulation with Iber (Q_sim)
Through the application of tests B1, B2 and B3 with Iber, the following total runoff values were obtained: p45 = 902,133.05 m³; p60 = 1,727,025.07 m³; and p98 = 3,684,071.36 m³.

2.5.2. Estimation of total runoff using the NC method (Q)
Following the NC method, the surface runoff (Q(mm)) produced by a determined precipitation (P(mm)) from NC was estimated. According to this method, first the potential retention (S) is obtained by means of the following formula:

\[(1) \quad S(\text{mm}) = 254 \times (100/\text{NC} - 1)\]

The direct runoff (Q(mm)) generated by the precipitation (P(mm)) is then calculated:

\[(2) \quad Q(\text{mm}) = \left[\left( p - 0.2*S \right)\right] \times 2/((p + 0.8*S))\]
And finally the total runoff ($Q_{mm3}$) is calculated taking into account the entire area of the Basin ($Am2$):

\[(3) \quad Q_{mm3} = Q_{mm} \times 10^{-3m} \times Am2\]

Following the NC method, $Q_{mm3}$ can be calculated both in distributed and aggregated form, which can be done in a GIS through raster operations, as we did in this work.

Applying the above formula in the study area ($A = 59,913,900 \ m^2$), for a value of $p = 98mm$ the following results:

\[S(\text{mm}) = 254 \times (100/92-1) = 22.09\]
\[Q(\text{mm}) = \left(98 - 0.2 \times 22.09\right)^{2}/\left(98 + 0.8 \times 22.09\right) = 75.71\]
\[Q_{mm3} = 75.71 \times 10^{-3m} \times 59,913,900\ m^2 = 4,536,269\ mm^3\]

$Q_{mm3}$ is calculated in the same way for the other precipitation values ($p = 45mm$, $p = 60mm$ (table 5)).

Table 5. Estimation of direct runoff by the NC method, based on historical precipitation values and land cover of 2014 (coverage B)

| $p$ | $S$ (mm) | $Q_{mm}$ | $Q_{m^3}$ | Área ($A$) |
|-----|---------|----------|----------|-----------|
| 45 mm | 22.09 | 26.28 | 1,574.427 | 59910 m² |
| 60 mm | 22.09 | 39.78 | 2,383.012 |         |
| 98 mm | 22.9 | 75.71 | 4,535.974 |         |

Source: Prepared by the authors, with data from Dal-Ré, 2003.

2.5.3. Nash-Sutcliffe criterium

As shown in formula 4, this index compares simulated values ($Q_{sim,i}$) with actual values ($Q_i$). Depending on the value that $E$ acquires, a criterion is issued on the fit of the model ($< 0.2$ insufficient; $0.2$ - $0.4$ satisfactory; $0.4$ - $0.6$ good; $0.6$ - $0.8$ Very good; $> 0.8$ Excellent ).

\[(4) \quad E = 1 - \left(\sum(Q_{sim,i} - Q_i)^2 / \sum(Q_i - Q_{average})^2\right)\]

These values simulated with Iber ($Q_{sim,i}$) were contrasted by means of the Nash-Sutcliffe test (formula 4) with the values estimated by means of raster operations using the NC method (formula 3) that is, for comparison purposes, we assume as observed data ($Q_i$) the obtenidos by the NC method, given its generalized use.

The test gives an $E$ value = 0.6876 so it is assumed that the fit between the results obtained with the model and those obtained using the NC method is Very Good (table 6).
Table 6. Validation of model results (Nash-Sutclif test).

| P     | P_{sim,i} | Q_{i}   |
|-------|-----------|---------|
| 45mm/h| 902,133.05| 1,550,878.00|
| 60mm/h| 1,727,025.07| 2,347,369.00|
| 98mm/h| 3,684,071.36| 4,468,128.00|

E = 0.68764048

Source: Prepared by the authors, based on the results of simulations with Iber and calculation of flows by the NC method.

In addition, an empirical evaluation based on reports and evidence from CONAGUA [23] on the occurrence of overflows in some points of the river was carried out, and the maximum water depth values at the registration points were compared with the critical and maximum SAHT values. We finding coincidence in the results.

3. Results and Discussion

3.1. Change of soil cover

The comparison of 1986 and 2014 coverages showed that the area of residential use and infrastructure increased by more than 3% per year, while the area of agricultural use (pasture and cropland) decreased by about 1% per year (table 2). Tree cover remained almost constant during the period 1986-2014, confined to parks and gardens, as well as in protected areas that have existed for several decades [28, 6].

Table 7. Maximum depth values in the register points (m).

| Register points | P1 = 45 mm | P2 = 60 mm | P3 = 98 mm |
|-----------------|------------|------------|------------|
|                 | A1: 1986   | A2: 1986   | A3: 1986   |
|                 | A1: 2014   | B2: 2014   | B3: 2014   |
|                 | A2: 1986   | B3: 2014   |
|                 | A2: 2014   | B3: 2014   |
|                 | A3: 1986   | B3: 2014   |
|                 | A3: 2014   | B3: 2014   |
| TA              | 0.86       | 1.87       | 3.45       |
|                 | 1.59       | 2.49       | 3.82       |
|                 | 85%        | 33%        | 11%        |
| PJM             | 0.99       | 2.33       | 4.03       |
|                 | 2.17       | 3.14       | 4.47       |
|                 | 119%       | 35%        | 11%        |
| C2P             | 1.21       | 2.61       | 4.02       |
|                 | 1.88       | 3.03       | 4.02       |
|                 | 55%        | 16%        | 0%         |
| IB              | 1.19       | 2.26       | 3.77       |
|                 | 1.93       | 2.90       | 4.24       |
|                 | 63%        | 28%        | 13%        |
| PO              | 1.37       | 2.76       | 4.38       |
|                 | 2.15       | 2.98       | 4.45       |
|                 | 57%        | 8%         | 2%         |

Source: Prepared by the authors, based on the results of simulations with Iber.

3.2. Effects of changes in land cover on maximum water depth values

As a consequence of changes in land cover, the mean values of roughness (n (1986) = 0.07; n (2014) = 0.11) and losses (NC(1986) = 85; NC(2014) = 89) have changed, thus altering the hydrological characteristics of the basin and the hydraulic response of the canals.

Table 7 and figure 3 illustrate the behavior of the water at each of the registration points. The
values of the minimum, critical and maximum levels of the SAHT are compared with the maximum water heights obtained in the 6 trials. Although with p45 there is no overflow at any of the recording points (Tests A1 and B1), the depth values are visibly greater in 2014 in a range of 55 to 119%, compared to 1986. With p60, the maximum depth values in test B2 exceed those of test A2 in all stations, since 8% in the PO point register to 35% in PJM (table 7). With p98, critical levels were exceeded at practically all recording points of both years (A3 and B3 Tests), and maximum levels were exceeded at JMP and C2P points, i.e., overflow occurs (figure 3).

![Figure 3](image)

**Figure 3.** Comparison of the water heights levels obtained in the Iber simulations, based on the results with the Iber simulation tests.

The following can be deduced from the analysis of the classified images: Changes in land cover between 1986 and 2014 altered the hydrological-hydraulic behaviour of the basin. The substitution of tree and shrub cover, as well as bare soil and agricultural use, to expand the land for residential and infrastructure use, decreased the capacity of water infiltration into the soil, while decrease too the interception by vegetation. Consequently, in 2014, the same rainfall regime generated greater surface runoff, greater volume of flow and greater hight of water in the main channel, thus increasing the risk of overflowing the Sabinal River.

As a consequence of unregulated urban growth, areas of natural runoff and flood plains were invaded in Tuxtla Gutiérrez, whose function is precisely to naturally regulate excess flow. These actions have altered the hydrological balance of the basin and have increased the degree of vulnerability of the population to extreme hydrometeorological events [29, 30].

Typically, hydraulic simulation models are statistically validated by comparing the observed flow values \( (Q_o) \) with the simulated flows \( (Q_{sim}) \) [31].
In our case, given that we do not have $Q_i$ values, we compare the validity of Iber’s numerical calculation method by contrasting the total runoff values that this model yields ($Q_{\text{sim},i}$) with total runoff values calculated using the NC method ($Q_i$), finding a Very Good fit level.

To do this, we compared the effect of simulated precipitation with that of real precipitations, we verify that simulated and real floods occur with the same precipitation threshold.

Therefore, we assume that the Iber simulation model yields good flow results and, together with the good definition of the DTM, allows us to make good estimates of water depths and heights in the riverbed.

In the simulations with Iber it was found that, as documented by CONAGUA [23], with rainfall greater than 90 mm, the Sabinal River overflows in some points, and with 60 mm, there is a high risk of overflowing the river. The results of the water heights levels at the registration points, obtained with the Iber simulation tests, were consistent with the critical and maximum values corresponding to the SAHT level stations; and the simulated overflows occurred in the sites reported by CONAGUA (tables 1 and 7). There is a good representation of the actual water heights reached in the river with a given precipitation.

Therefore, the empirical validity of the proposed methodology is verified, confirming its usefulness for analyzing flood areas and comparing the effect of a given precipitation on different terrain conditions (figure 2).

The scale of the working files is very important in hydraulic models if you want to guarantee a good level of precision in the results [32]. In our case, an DTM with good resolution and accuracy was generated using LIDAR data, which helped us to obtain good results in hydraulic simulation.

This methodology, although not practical for real-time monitoring of height levels, flows and total runoff volume, can serve two purposes: 1) as a tool for the configuration and feedback of hydrometeorological warning systems, and 2) to analyze the risk of overflows and flooding in localities lacking infrastructure for real-time monitoring of water height levels, taking advantage of records from nearby rainfall recording stations. There are a large number of rural basins, as well as small urban basins that do not have gauging sites or manual or automatic stations to record water height levels. In these cases, the proposed methodology can be very useful, since it does not require large technical inputs or information.

The comparison of three rainfall event (45, 60 and 98 mm) with two land cover conditions (minor and major urbanization in 1986 and 2014, respectively) leads us to warn of the urgency of applying effective control measures in urban planning. Priority should be given to the recovery and maintenance of tree cover, urban gardens, restoration of wetlands, recovery of riverbanks and flood plains, etc. If the trend towards greater soil impermeability continues, it will be necessary to invest heavily in urban infrastructure for rainwater collection, control and conveyance, as well as other environmental effects.

4. Conclusions

The increase in urban-residential coverage in Tuxtla Gutiérrez at the expense of tree, agricultural and grassland coverage has reduced the capacity for water infiltration in the soil and interception, so that with extreme rainfall, the amount of runoff is greater, which increases the risk of overflowing the Sabinal River.

Remote sensing and simulation models, together with GIS tools, are very valuable resources for characterising the territory and analysing flood events.

The proposed methodology can be useful for detecting flood risk, based on certain precipitation values, thus providing feedback to flood risk warning systems.

The behaviour of a basin can be reproduced even with limited resources. Our model could be useful for flood risk mapping small rural communities that lack infrastructure for real-time monitoring of water height levels.
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