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El Niño in the City: Vulnerability assessment in Tijuana during the winter of 1997-98

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RESUMEN

Un estudio piloto de la hidrología superficial de las cuencas que incluyen a la ciudad de Tijuana y la caracterización por medio de un Sistema de Información Geográfica de los riesgos resultantes de las precipitaciones extremas asociadas al event de El Niño de 1997-98, permiten una evaluación y categorización de las acciones requeridas para mitigar los peligros de futuros eventos meteorológicos extremos.

PALABRAS CLAVE: El Niño, Tijuana, evaluación de peligros, riesgos naturales.

ABSTRACT

A pilot study of the hydrologic response of the basins that include the city of Tijuana and a characterization by means of a Geographical Information System of the hazards resulting from the considerable rainfall brought about by the 1997-98 El Niño, provide an assessment and classification of the actions needed to mitigate the dangers of future extreme meteorological events.

KEY WORDS: El Niño, Tijuana, risk assessment, natural hazards.

1. INTRODUCTION

The city of Tijuana has experienced a very rapid urban expansion since the 50's, but the absence of a true planning perspective combined with an inadequate topographical site have exposed a large number of its inhabitants to natural risks. Hydrologic processes like rainfall and runoff are most common and their periodic recurrence have caused considerable human and material losses.

The 1997-98 El Niño event was used, in a COLEF-IRD joint project, as a pilot study to collect real-time information for studying its urban effects through the use of a Geographic Information System (GIF). The main purpose was to carry out an integral analysis of the city of Tijuana during a rainy winter, including space and time distributions of the rainfall, zoning the effects of El Niño on the urban web, modeling the surface runoff, and documenting the signs of malfunction of the urban watersheds (Figure 1) to construct a global vulnerability assessment.

An event is a danger that may hit the city and unleash punctual or chain reaction incidents. The event may be either natural or technical. The vulnerability is the propensity of the entity, or parts of it, to suffer damages during an event. That event may be destructive, considering that the intensity of destruction is highly related to the self-protection of the entity, so it can be said that the vulnerability is a result of the underdevelopment, or to be more accurate, "underconsolidation" of the city or parts of it, in the understanding that those parts may themselves endanger others. The danger and the vulnerability together conform the risk, or the total probability to suffer material losses or human injuries, the second one being usually more costly in less developed countries.

The response to an El Niño event proceeds in three principal phases. Initially, much time is spent gathering information, and in thinking, discussion, organization, conditioning, and making decisions under the best conditions of certainty available. The second phase arrives suddenly with the onslaught of the climatic event, and in the case of the city of Tijuana, it is made up of a series of more or less acute crises. In a time varying from 30 minutes to two hours, the principal incidents occur: flooding, slumps, etc… In the following 24 hours the city is in full emergency activity. During the week following the event, local authorities carry out the prioritary clearing and cleaning. The successive repetition of crises, such as weekly returns of severe rains, introduces a new element that pushes the city into a permanent state of crisis, where the administration is no longer able to manage and acquires more a role of a full-time fireman, a state that induces a certain general lassitude: the catastrophes are no longer exceptional, but become part of everyday life.

The city remains on alert during a few weeks after the rains until, quickly, both the clouds and the front line news

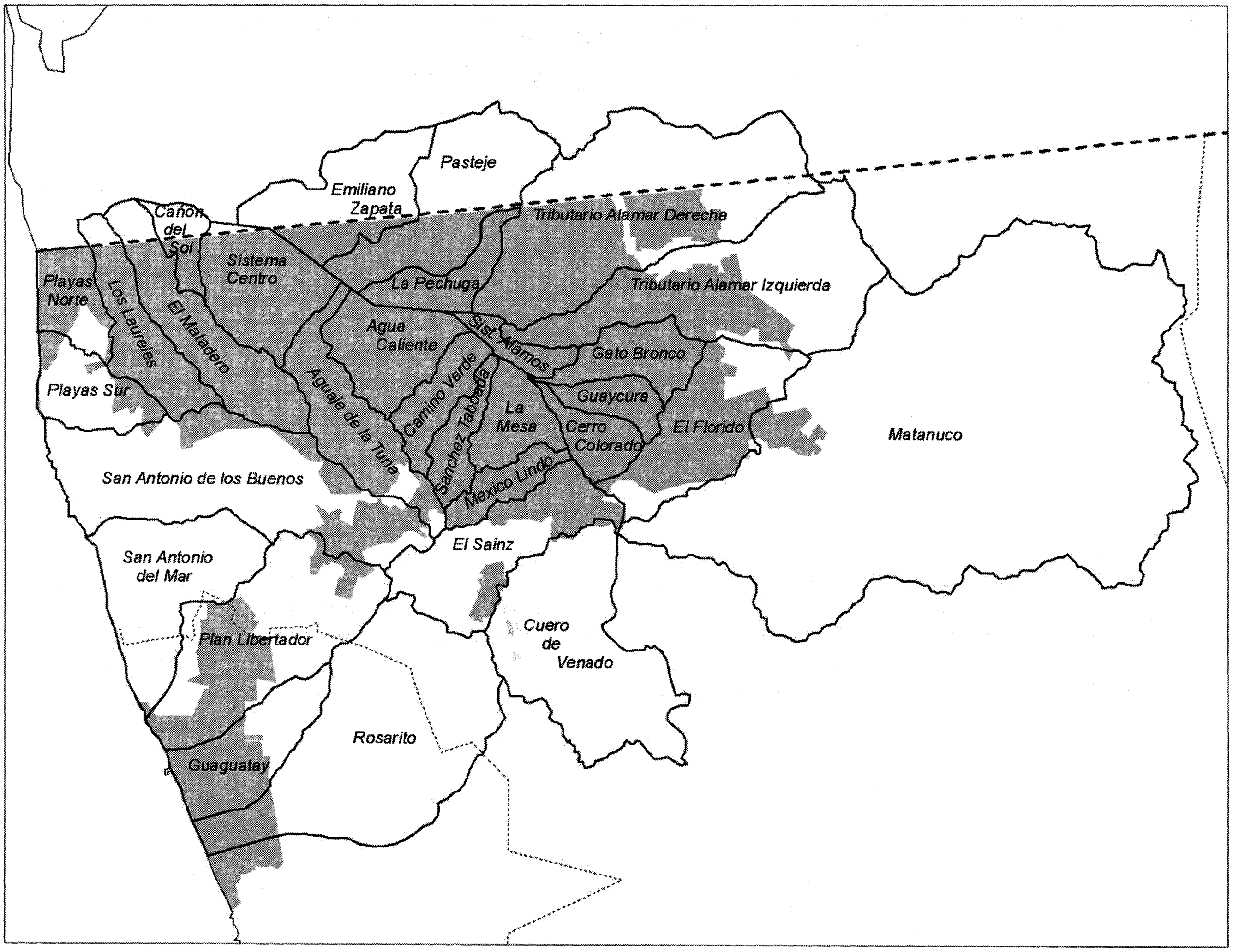


Fig. 1. Location of the Tijuana wathersheds.

disappear from the city's horizon. Logically, the city should then turn onto a final El Niño phase and normality, but the lack of a defined activity makes it difficult to define this last post-El Niño period.

2. ANALYZING THE RAINFALL

2.1. The 97-98 El Niño rainfall characterization

The climate of Tijuana is subtropical, off a western continental slope. It is a dry climate with annual average rainfall of 235.3 mm (climatic year from July to June, series 1950-1998) and a typical Mediterranean distribution with predominant winter-spring rainfall, concentrated between November and April. This average hides important variations (Figure 2): During the 40 normal (or non-El Niño) years, the yearly average rainfall was about 206.9 mm, but the 9 years with an El Niño produced an average of 361.6 mm, a variation of 74.8 percent.

The spatial distribution of the winter rainfall in Tijuana was monitored through a network of 27 rain-gauges installed and operated from October of 1997 until June 1998. With a yearly total of 579.4 mm, the station at La

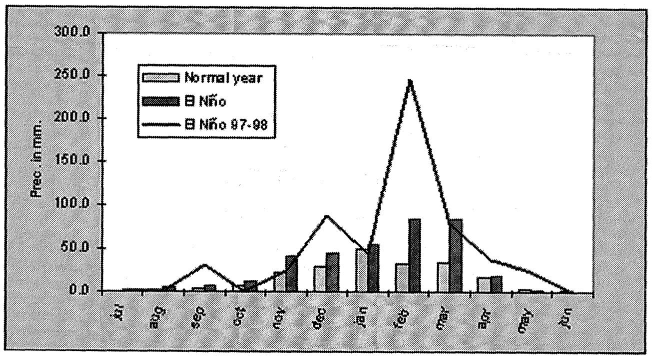


Fig. 2. Comparison of rainfalls at La Presa Rodríguez.

Presa Rodríguez received the largest precipitation registered since 1950, 2.5 times the average rainfall, almost triple that of a normal year, and 1.6 times the average of the 9 last El Niño years.

The monthly distribution of this El Niño episode is clearly different from earlier events, since it showed two clearly defined maxima. The first and smallest happened in September, related to tropical storm Nora crossing the Baja California peninsula 100 km south of Tijuana. The second maximum occurred during February, when major storms brought 247.5 mm, three times the average rainfall of an El Niño February month, the second rainiest month in the entire history of Tijuana, and exceeded only by January 1993. The final phase was comparable with the normal evolution of most El Niño periods.

The rain distribution (Figure 3) showed significant variations in a northwest-southeast direction, following the main topographic features. The two areas with the largest rainfall were located to the southwest of the Tijuana River, where 580 mm were registered and at the northeastern corner of the western slopes of the peninsular range, where rainfall reached almnost 700 mm. By contrast, only 400 to 480 mm were recorded at the coast, and 460-500 mm in the central portion of the city.

2.2. The 1997-1998 El Niño significant daily events

Eleven events with a daily rainfall above 20 mm were recorded, which caused significant runoff, and were also correlated with the development of surface morpho-dynamic processes. The strongest event occurred on February 7, 1998 (Figure 4). It featured a strong maximum of 60.3 mm in 24 hours over the southwestern hills, surrounded by a wide area with amounts greater than 40 mm in the central city and the southwestern riverside, the same area that received the largest precipitation during the two earlier events. Two islands of relatively minimum precipitation were also identified, one towards San Diego bay, and the other one in the southeastern corner of the city. Finally, the precipitation increased gradually towards the hills on the American side of the border. Intense rains were observed, mostly within six hours, with a peak of approximately 30 mm at 3:00 AM, falling on an already saturated terrain.

In summary, the main causal factors in the outbreak of catastrophic flooding turn out to be the intensity and amount of water accumulated in a short period of time, one day or less. Rains that can have catastrophic consequences take place with relatively high recurrence, less than 4 years for rainfall between 40 and 50 mm; about 9 years for rains between 50 and 60 mm; and 12 years for rainfall between 60 and 70 mm.

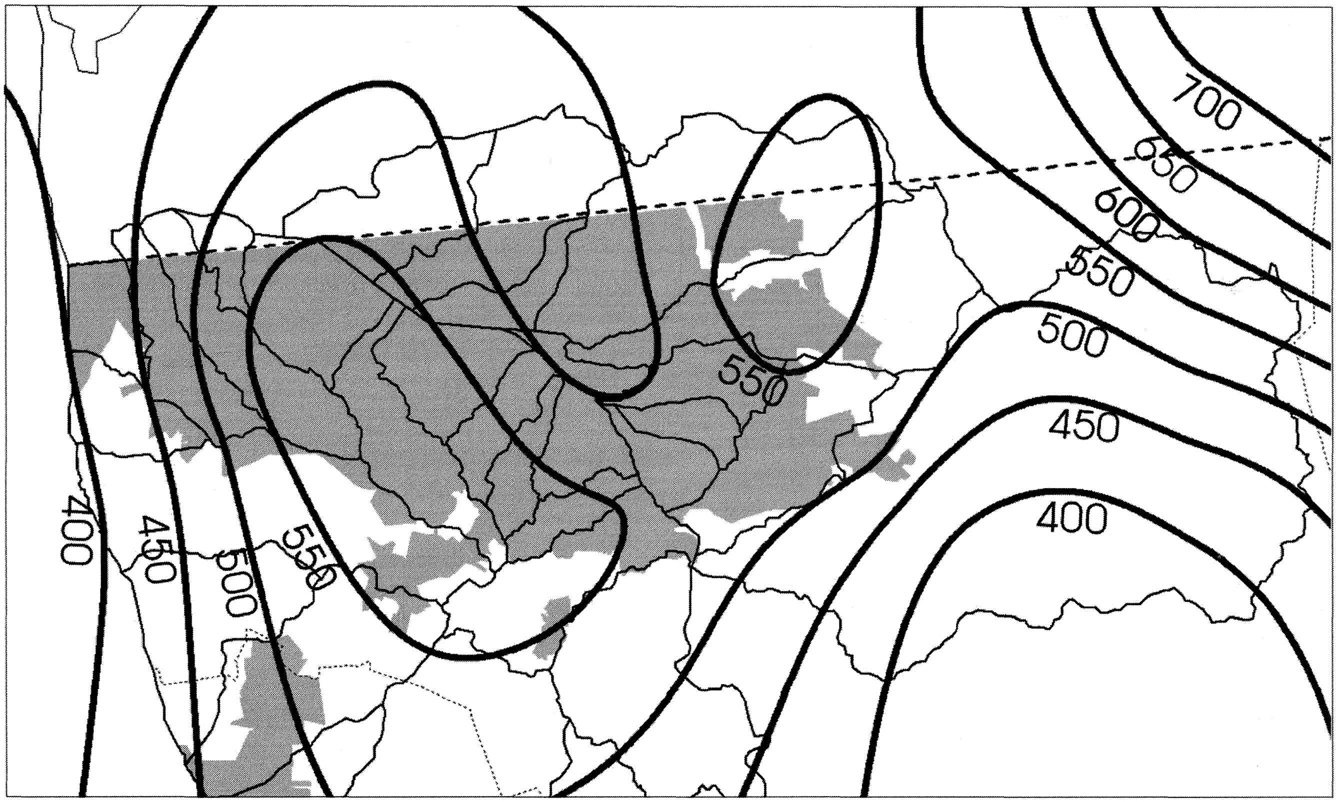


Fig. 3. Total rainfall in Tijuana during the 1997-98 El Niño.

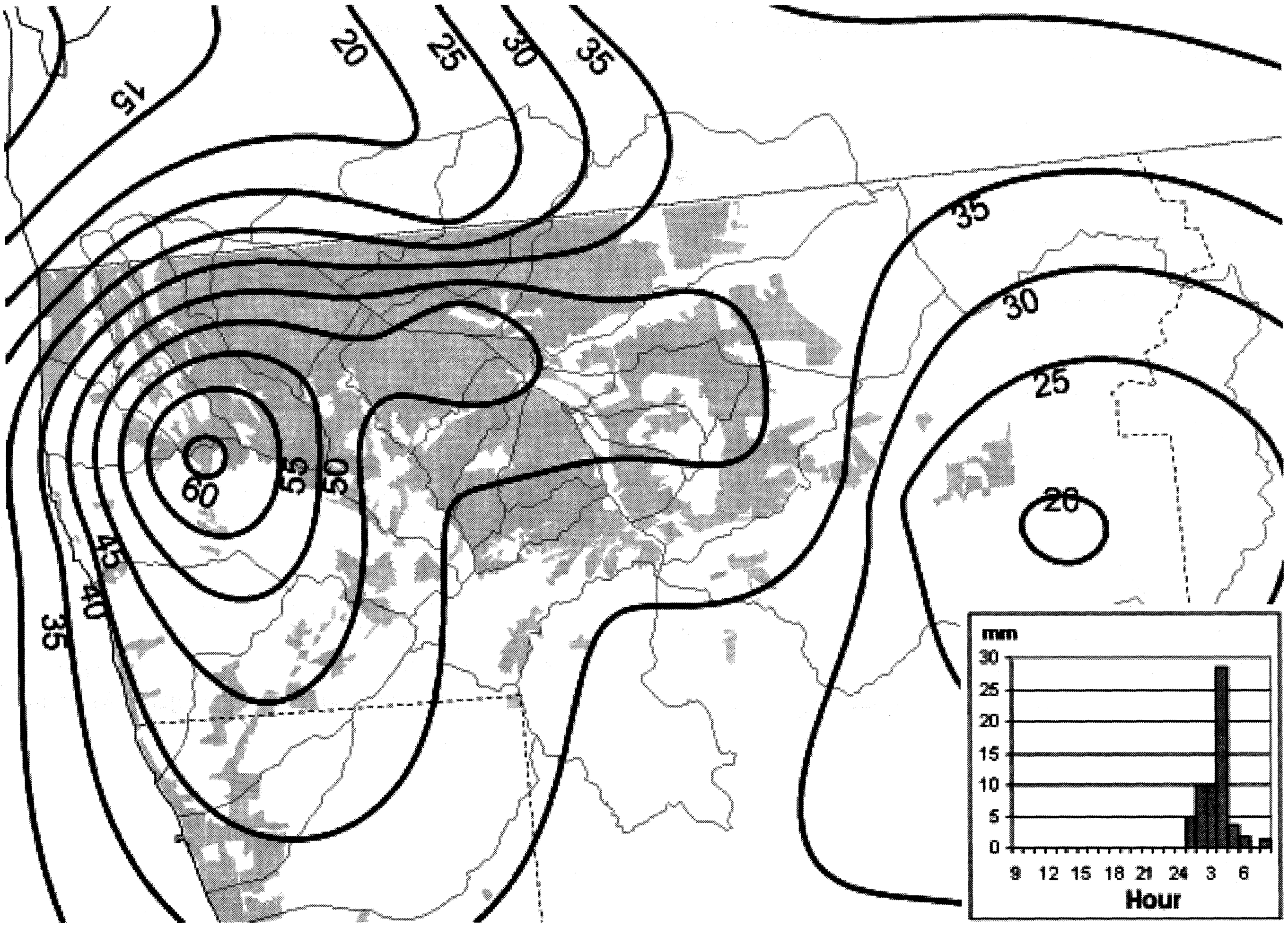


Fig. 4. Rainfall distribution on February 7, 1998.

Although the El Niño phenomenon is correlated with strong rains in Tijuana, the historical archives show that intense rainfall, monthly as well as daily, can occur at any time, in both normal and/or El Niño periods. In nearly 50 years only two events exceeding 70 mm were recorded, neither of which were during El Niño; the largest took place in January 1993.

The risk of flooding and slope motions thus exist every winter and one of the high-priority tasks should be the installation of a network of rain-gauges (ten should suffice) within the city, to register the space and time variations of the rainfall, in order to develop an effective alert system.

3. SPATIAL ANALYSIS: THE IMPACT OF EL NIÑO IN THE CITY

The impact of climatic events in Tijuana cannot be assessed through a single agency because the coverage of the crisis became very complex given the number of simultaneous incidents and their different aspects. Among the various sources of information, several appeared too weak and others unworkable, but some were useful. We examine three of them:

1. *City's emergency hot-line:* Although a first-time experiment, it received more than a thousand calls. Despite the need to access a phone line to declare the emergency and the repetition of many calls, it provided an interesting view of the impacts on the city. This database allowed to map, categorize, and establish causal relation amongst many of the incidents. We constructed five series of maps to classify each of the major events. After homogenization and validation, a codification of the different facts in four aggregation levels was made, identifying the following causes:

- hydraulic overflow by flood or stagnation

- alluvial deposits like mud, sand or blocks contributed by hydraulic currents

- slope dynamics, including slides of houses, walls, and trees by gravity effects, slumpings or solifluction of surface materials, etc…

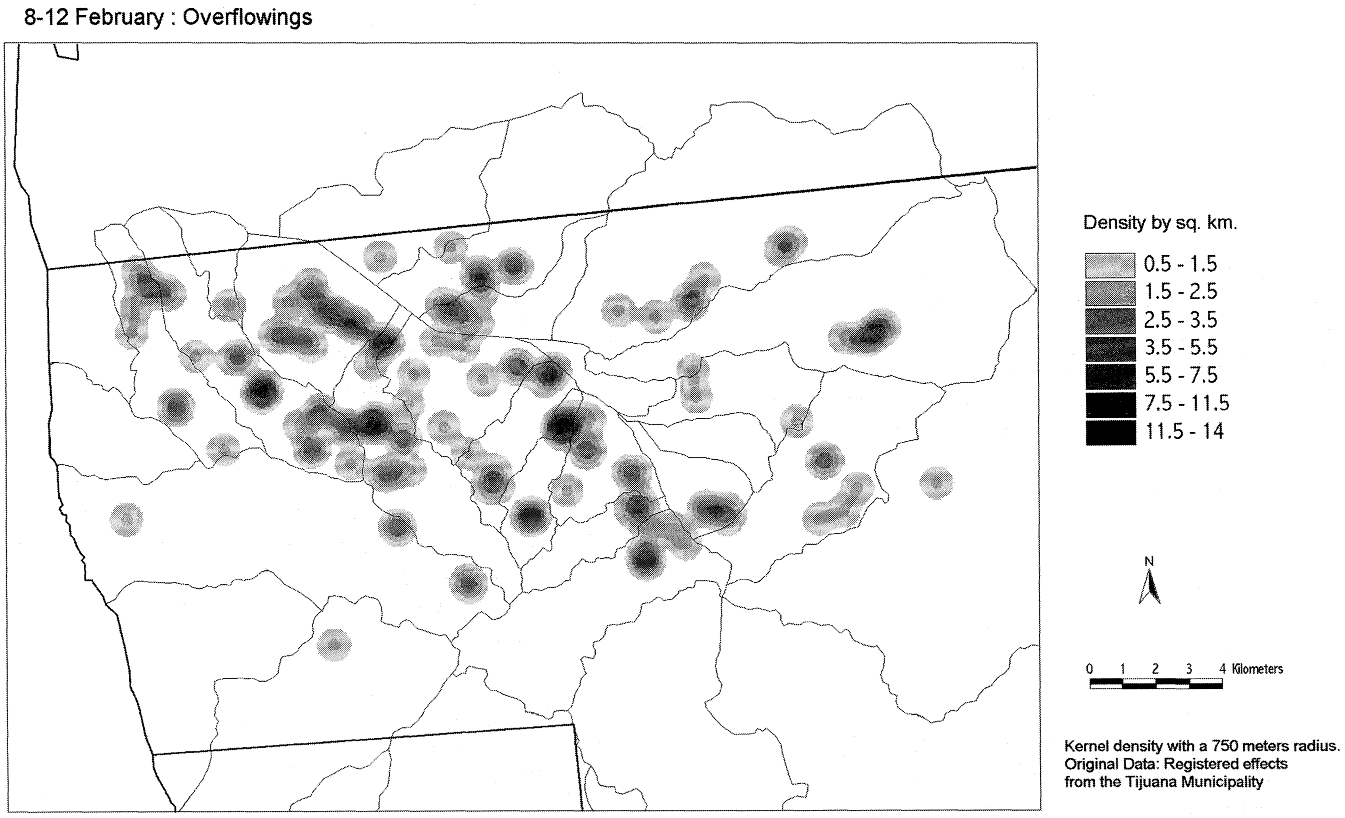
- linear erosion caused by hydraulic scouring.

Some difficulties occurred with multiple-cause impacts, but the test allowed to visualize and understand a considerable portion of the facts in the inventory. The density maps, realized by a kernel density technique, illustrate the distribution of the phenomena for each of the four types of dynamics defined above. As an example, the 429 phone calls registered between February 8th and 12th reported:

- Overflows (Figure 5): Mainly in the southwestern city, very common in the lower parts of the river catchments, where water overflows or stagnates. Interestingly, problems also occur in some precise sites of the upper parts of the hydraulic network. On the northeast side of the valley overflows are much less frequent, although two zones stand out in the lower part of La Pechuga, and in the southern Alamar system. The remaining cases are very isolated.

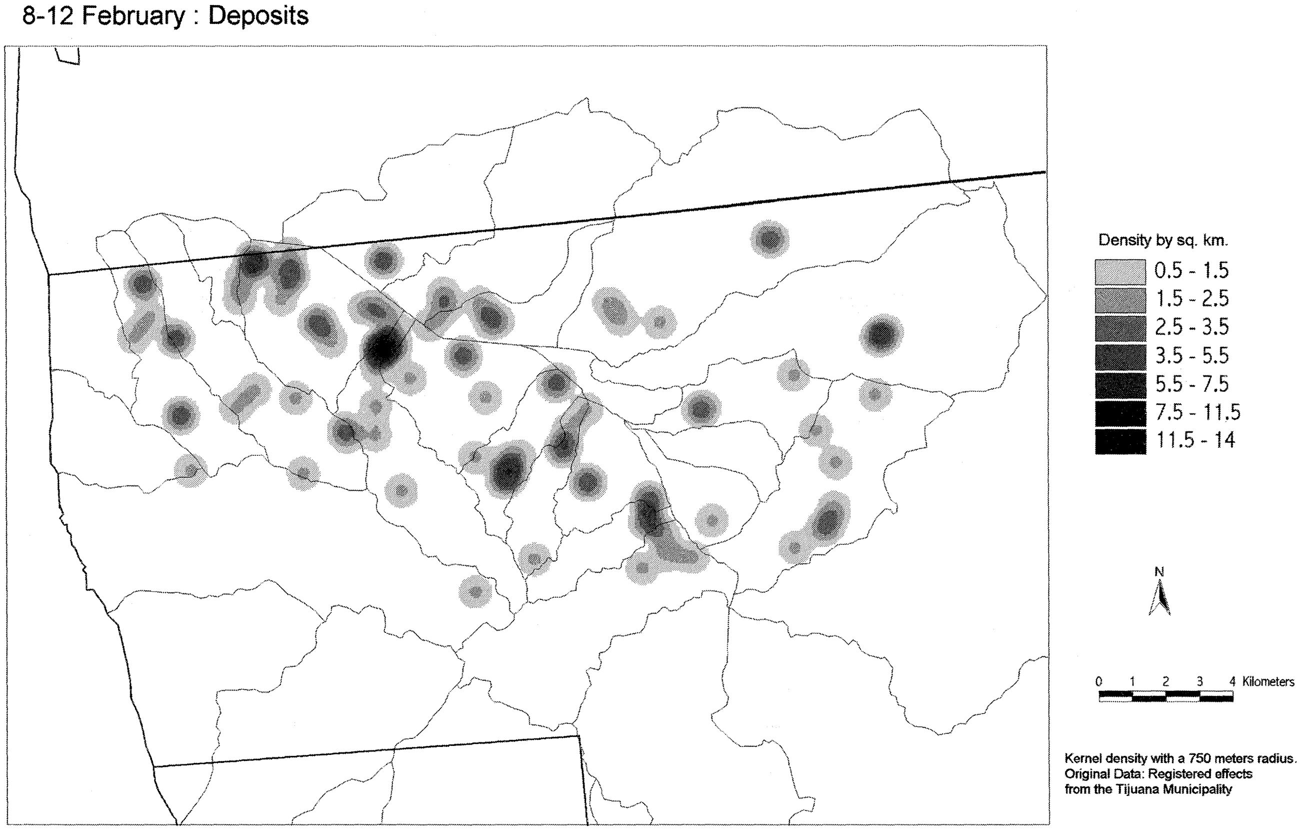
- Alluvial deposits (Figure 6): Mostly observed in the lower part of Aguaje de la Tuna, around the sedimentation tank of the same name. This 2340 m^3 structure was frequently filled with debris, with consecutive overflowing of water, mud and sediments along several downstream streets. Other catchments affected included Sánchez Taboada, Camino Verde, and the México Lindo watershed, which lack this type of infrastructure. In the central system, the sedimentation tanks carried out their task perfectly. Outside of these areas, few similar damages occurred.

- Slope dynamics (Figure 7): The reports are much more numerous than in the previous case, with a total of 176 cases recorded. The catchment that seems most affected, at least in terms of covered area, is Matadero, where the entire inhabited zone suffered such motions. Areas of high concentration also appear in the catchments of Aguaje de la Tuna, and in the lower parts of Sánchez Taboada and México Lindo. In the northeast of the Tijuana River, the


8-12 February : Overflowings

Kernel density with a 750 meters radius.
Original Data: Registered effects
from the Tijuana Municipality

Fig. 5. Overflows between 8 and 12 February, 1998.



Kernel density with a 750 meters radius.
Original Data: Registered effects
from the Tijuana Municipality

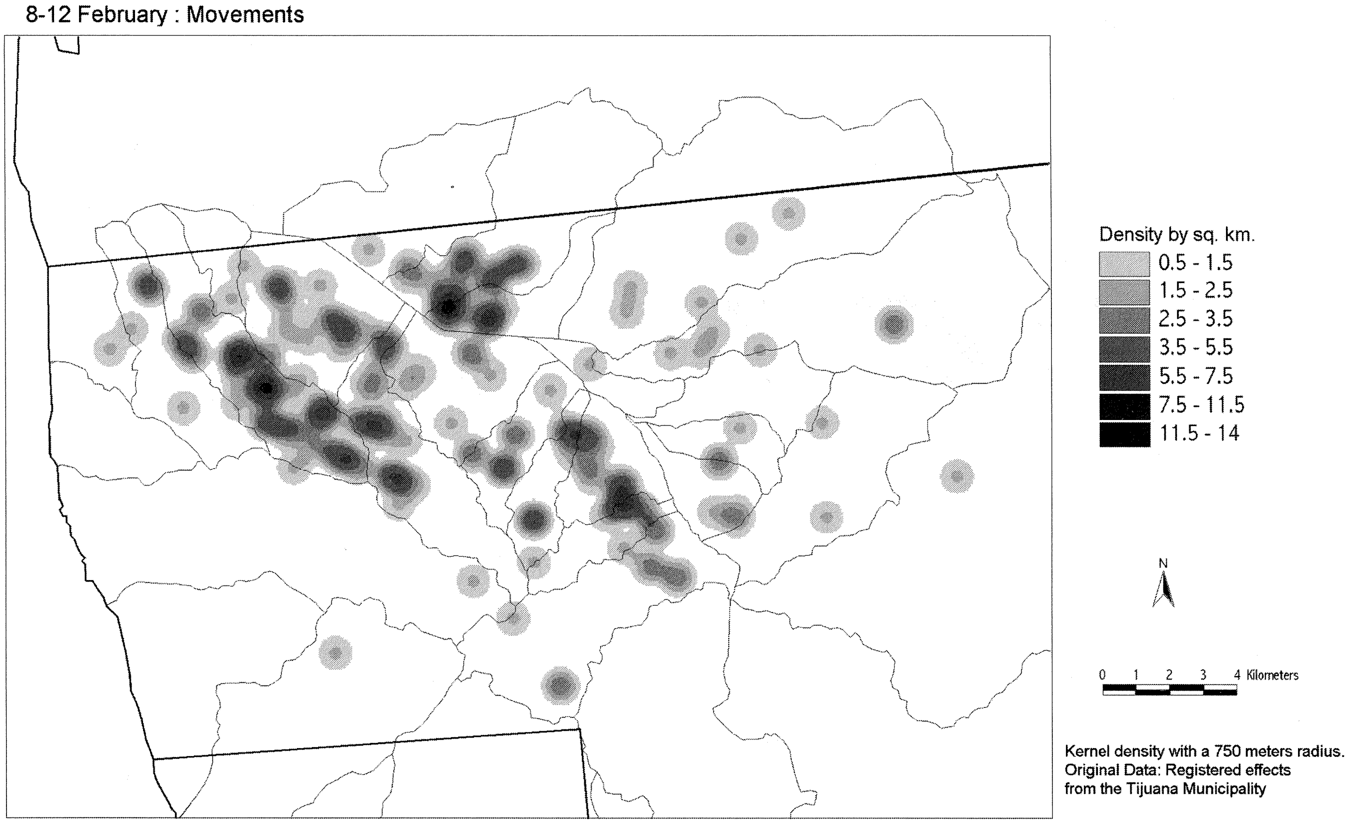
Fig. 6. Events of alluvial deposition between 8 and 12 February, 1998.

discharge of the Pasteje constitutes one of the most serious threats.

Damage density varied greatly, with seven catchments suffering the most harm (> 4,71 facts by km²), eight with moderate damage, and 11 with slighter damages. The number of reports appeared unrelated to the population density. The Aguaje de la Tuna catchment had almost twice as many reports as its neighbor Matadero, which has twice the population density. Six watersheds reported more than one call for each 1000 inhabitants: Matadero, Camino Verde, Sainz, Pasteje, Los Laureles and the Central System.

2. *The shelters:* Nine shelters were in operation during the critical moments, with a total capacity for 2066 people. They represent, in fact, the usual answer that the city offers rainy winters. People showed up quickly after the first strong rains, either on their own, or through an evacuation ordered in response to a supposed situation of danger. A small survey was performed by the municipal DIF (Integral Development of the Family) with family heads allowed to define some characteristics of these 'refugees'. Several indicators, such as the lack of explanation for coming into the shelters or where they came from, indicate that the 122 families adding up to 560 persons inadequately represent the total affected population. The analysis of socio-demographic parameters shows that they represent the most marginalized sectors of the population. A great majority are immigrants from other parts of the country, their marital status shows great informality, but half of them had been settled in Tijuana for more than five years. They report a low education level, and the families counted on about 540 pesos per week (about 60 $US at the 1998 exchange rate) to sustain an average of 4.6 people. The precariousness of their situation is underlined by the descriptions of their houses, mostly of self-construction (wood, recycled materials, cardboard roofs and walls, dirt floor, etc...). Half of the families appeared to own their humble homes, which points to the well-known problem of land invasions on dangerous areas in Tijuana.

3. *The press:* Figure 8 illustrates the amount of information in the regional newspaper 'El Mexicano' during February 1998. This newspaper, with a well-known communitarian approach, focused first on personal damages. 'El Cambio' limited its coverage mostly to the description of actual facts. From the press stories that made



Kernel density with a 750 meters radius.
Original Data: Registered effects
from the Tijuana Municipality

Fig. 7. Events of slope dynamics between 8 and 12 February, 1998.

references to location, a georeferenced database by buroughs (colonias) was made. Four maps were constructed, the first representing the importance given to the reported facts as measured by the size of the article, and three mapping the sort of damages to materials, people, and services.

The newspaper reports were mostly accurate (Figure 9) for punctual events like slope dynamics, human and material lost, and the sum of the stories provides a broad and true description of the incidents. Some distortion of the information was detected in stories related to two parts of the city: Zona Norte and Zona Río undergo year after year floods that disturb the traffic; although verified, these journalistic accounts cannot then be associated with exceptional rains. On the other part, El Florido was constantly mentioned, but damages there consisted mainly of interruption of electricity and potable water service. In absence of pavement, numerous streets were covered by mud, which caused traffic congestion and kept certain zones out of reach, but nothing truly overwhelming occurred in this watershed.

Several smaller zones, not necessarily of lesser visual importance, are distributed on the map. Landslides developed in isolated form in the Guerrero quarter, Cañón Miramar, El Mirador, Cumbres del Rubí and Llamas Amaya. The lower part of the México Lindo catchment is included within the small areas that sustained severe damage; it was in fact the neuralgic point of the city, where death and desolation added to the damage.

4. MODELING THE RUNOFF

The area of Tijuana is covered by 30 elemental or composite catchments, mostly urbanized. Each constitutes an independent hydrologic entity, and represents a unique and homogeneous environmental unit that constitutes the logical basis for all programs aimed at controlling runoff processes.

4.1. The modeling concept

An Athys-Mercedes spatial conceptual model that operates on the base of regular meshes was used to represent surface runoff. The model uses the principle of 'additivity' of contributions from the different meshes to reconstruct the resulting hydrogram in selected outlets. The different functions of the model are integrated by means of a square pixel

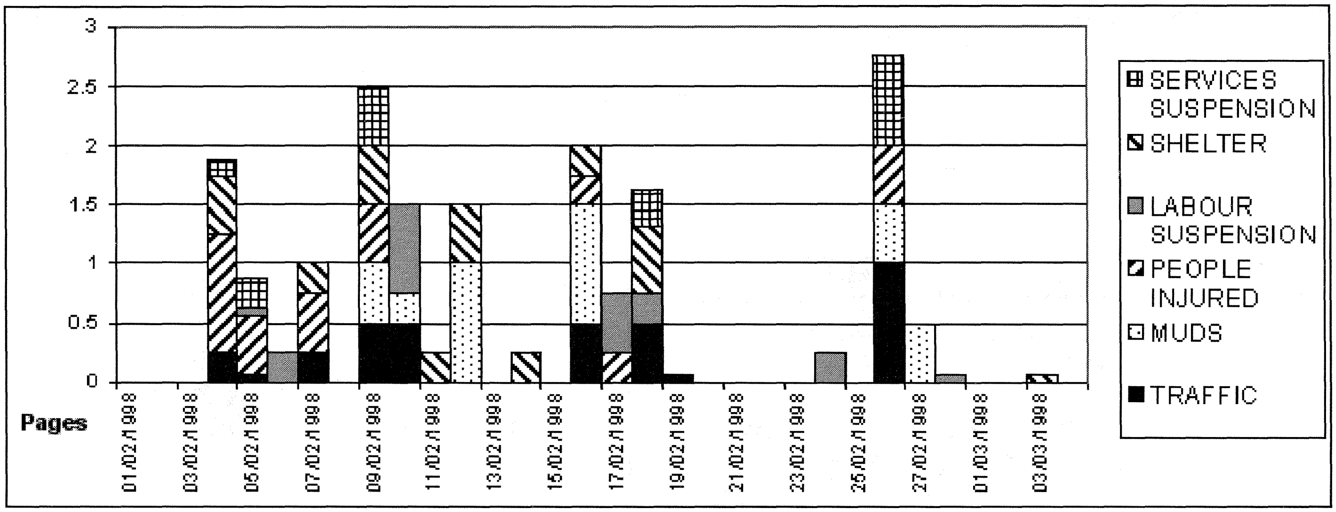


Fig. 8. Typology of events reported in El Mexicano during February 1998.

Cartography of the events registrated between the two newspapers during February 1998

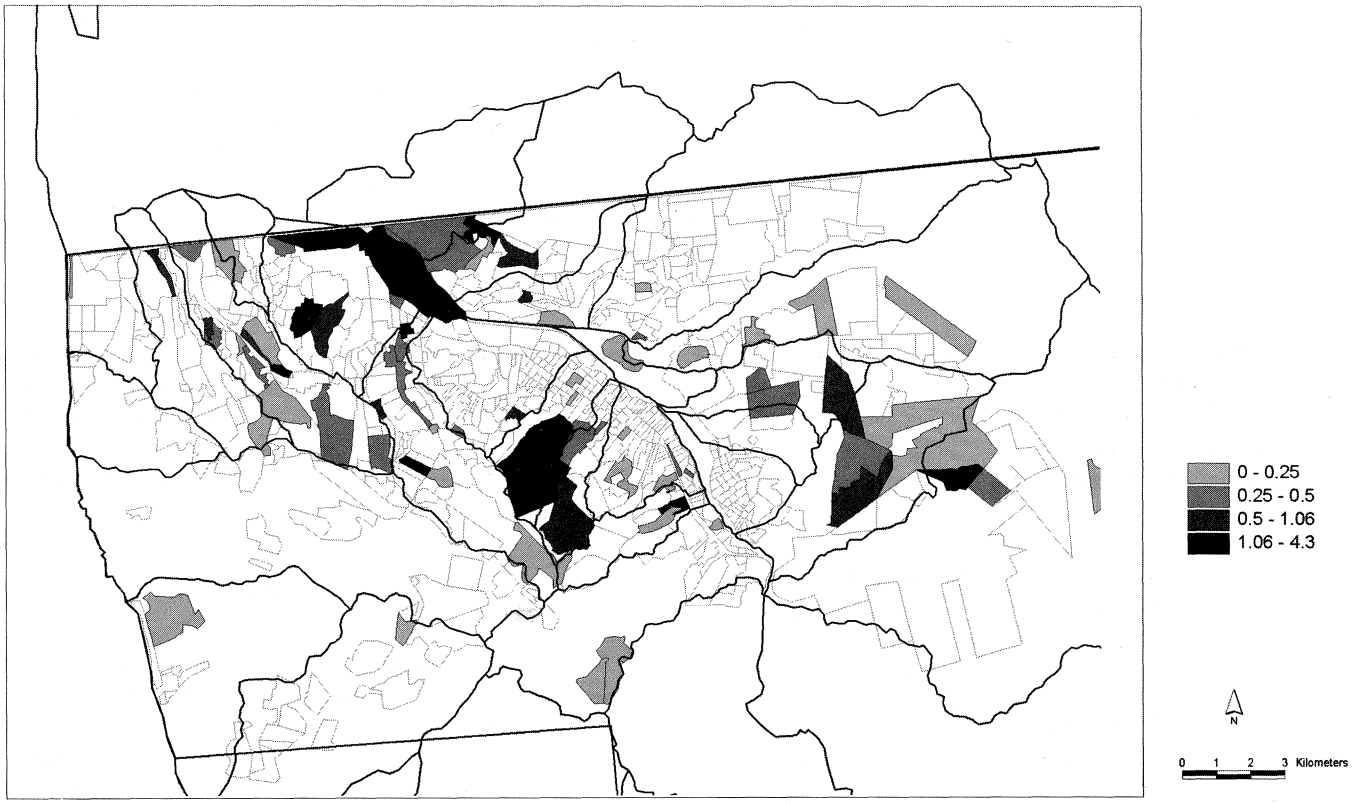


Fig. 9. Location of events reported by Tijuana newspapers during February 1998.

matrix over the space with a pixel resolution of 90 meters in our case. Four main elements have been selected to carry out this modeling process: the rainfall, the topography, the type of land use, and the hydrological conditions of the ground-underground. From these data, four layers of the hydrologic process were constructed: the daily rainfall, the drainage matrix, the production function, and the transfer function. The calibration was carried out in "Aguaje de la Tuna", where observations of the level, speed and duration of the flooding runoff were recorded in a concrete channel. We applied this procedure to the 18 in Tijuana, for each of the 6 major rainfall events registered during the 97-98 winter period. The results of the modeling process are presented as hydrograms, with the maximum peak flow in m^3/sec, the duration of the runoff in hours and the total volume in thousands of cubic meters.

4.2. The results of the modeling process

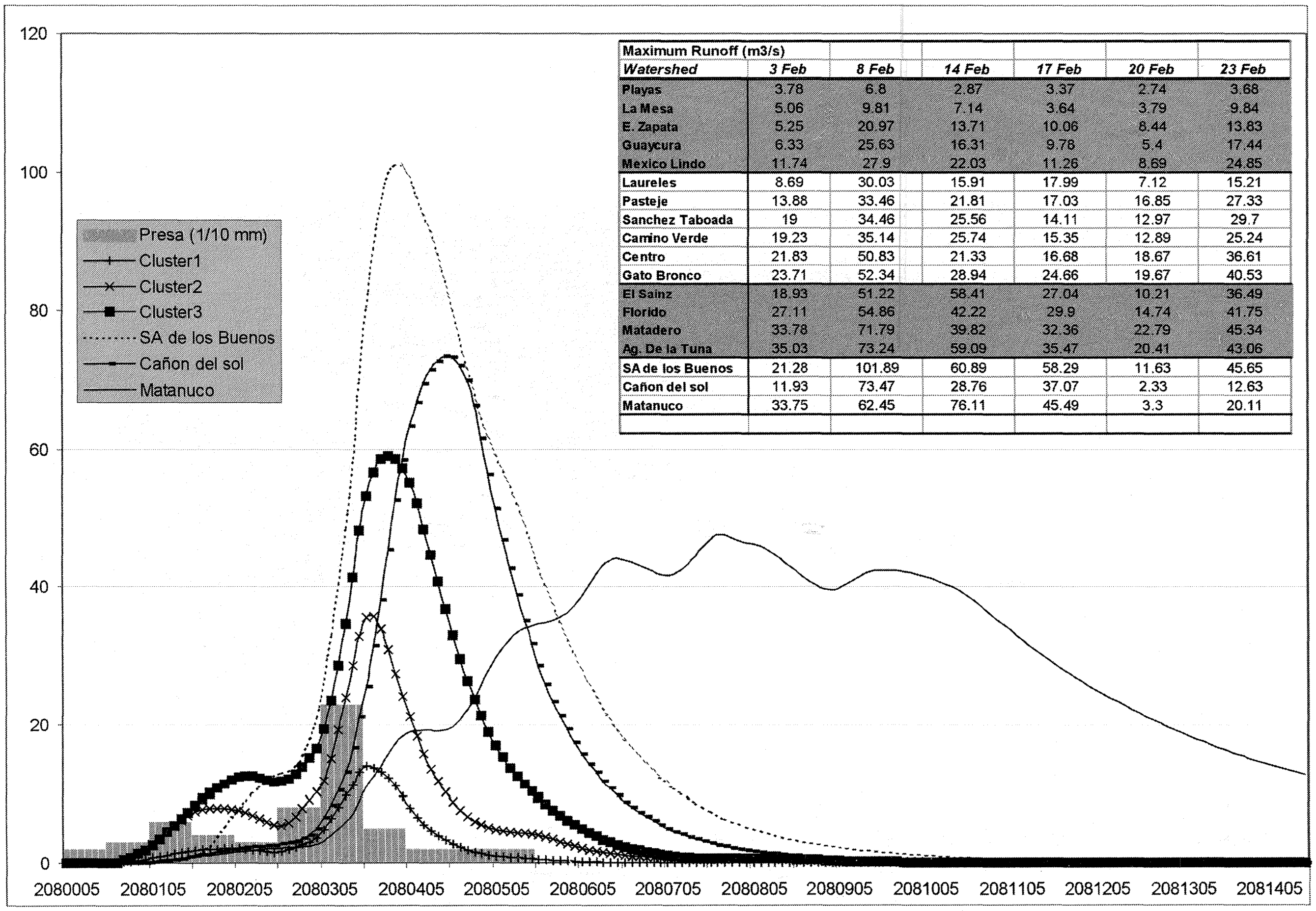
A clustering of the data extracted from the model provided three main groups (clusters) of urbanized catchments with relatively homogeneous runoff behaviors. Each group is represented with its resulting hydrogram, calculated with an unweighted average of its different components.

- Cluster 1 represents catchments with a rather stable runoff: Playas, La Mesa, Emiliano Zapata, Guaycura.
- Cluster 2 regroups catchments with an intermediate behavior such as México Lindo, Sánchez Taboada, Camino Verde, Pasteje, Los Laureles, Sistema Centro y Gato Bronco.
- Cluster 3 is the group of the unitary basins with the strongest runoff processes, like El Sainz, Aguaje de la Tuna, Matadero y El Florido.

In addition, three basins with very low urban development, Cañón del Sol, San Antonio de Los Buenos and Matanuco, showed a singular behavior, very similar to that of natural catchements.

The flooding event of February 8th, 1998

From February 3rd to February 8th, rainfall was light, with less than 12 mm recorded on the 6th. Stronger rainfall began at midnight on the 7th, ending with a cloudburst of 30 mm at three in the morning of the 8th. The three composite urban groups behaved exactly in the same way (Figure 10); the speed with which the flows increased is typical of the so-called 'oued' in Mediterranean areas: the response is very rapid, with the flow multiplying by five-fold within and hour and a half after the downpour. The flood management for these basins then requires a response to an increase of river flow within a very short delay - but with different flow peaks



Maximum Runoff (m3/s)						
Watershed	*3 Feb*	*8 Feb*	*14 Feb*	*17 Feb*	*20 Feb*	*23 Feb*
Playas	3.78	6.8	2.87	3.37	2.74	3.68
La Mesa	5.06	9.81	7.14	3.64	3.79	9.84
E. Zapata	5.25	20.97	13.71	10.06	8.44	13.83
Guaycura	6.33	25.63	16.31	9.78	5.4	17.44
Mexico Lindo	11.74	27.9	22.03	11.26	8.69	24.85
Laureles	8.69	30.03	15.91	17.99	7.12	15.21
Pasteje	13.88	33.46	21.81	17.03	16.85	27.33
Sanchez Taboada	19	34.46	25.56	14.11	12.97	29.7
Camino Verde	19.23	35.14	25.74	15.35	12.89	25.24
Centro	21.83	50.83	21.33	16.68	18.67	36.61
Gato Bronco	23.71	52.34	28.94	24.66	19.67	40.53
El Sainz	18.93	51.22	58.41	27.04	10.21	36.49
Florido	27.11	54.86	42.22	29.9	14.74	41.75
Matadero	33.78	71.79	39.82	32.36	22.79	45.34
Ag. De la Tuna	35.03	73.24	59.09	35.47	20.41	43.06
SA de los Buenos	21.28	101.89	60.89	58.29	11.63	45.65
Cañon del sol	11.93	73.47	28.76	37.07	2.33	12.63
Matanuco	33.75	62.45	76.11	45.49	3.3	20.11

Fig. 10. Synthetic hydrograms from automatic cluster classification.

(14, 35, 59 and 102 m^3/sec) depending on the size of the drainage basin.

But the surface of the catchement is not a decisive factor. The Pasteje, for example, has the largest drainage surface, but is found in Group II with intermediate flows, because a large proportion of its area remains unoccupied. Group I, with the smallest danger of surface runoff, includes four basins. Of these, Playas and La Mesa present little danger because of their small size; Guaycura and Emiliano Zapata remain undeveloped upstream, the former because its bi-national nature protects it from total urbanization and the later because its upper part is located near 'Cerro Colorado', where strong slopes have prevented urban growth.

The remaining basins constitute areas of territorial reserve for the future expansion of Tijuana, but they already show various states of urbanization. The 'Cañon del Sol' behaves in a similar fashion to the less urbanized watersheds, with a buffer effect retarding the flood curve by about 40 minutes. San Antonio de los Buenos is in a process of recent, diffuse, urbanization and presents very similar dynamic to the strong flows of Group III. A careless urbanization of this basin could induce very dangerous flows in the future, but the natural configuration of this basin, with a wide natural channel and a direct outlet into the Pacific Ocean, should contribute to reduce future threats. Matanuco is the basin that remains in its most natural state with clearly natural hydrological processes and a very low level of urban modifications. The increase of the flows in this basin is slow, peaks take up to five times more to develop than in any of the other basins and, in spite of its large surface area, the response of the Matanuco is much slower and smaller, reaching only 47 m^3/sec, an amount very similar to those of Group II.

5. A RISK ASSESSMENT PROCEDURE

5.1. Determination of threshold factors

An aggregation process was done for each catchments basin by combining statistical and geographical methods in the GIS, for all geo-recorded events, which were later reclassified according to their morpho-dynamic characteristics. The graphics for February 7 are very illustrative (Figure 11). It relates the rainfall to the runoff mean coefficient, with the symbol size being a function of the density of the events which, in turn, are related to the surface of the urban development. The catchments with fewer events are in the lower-

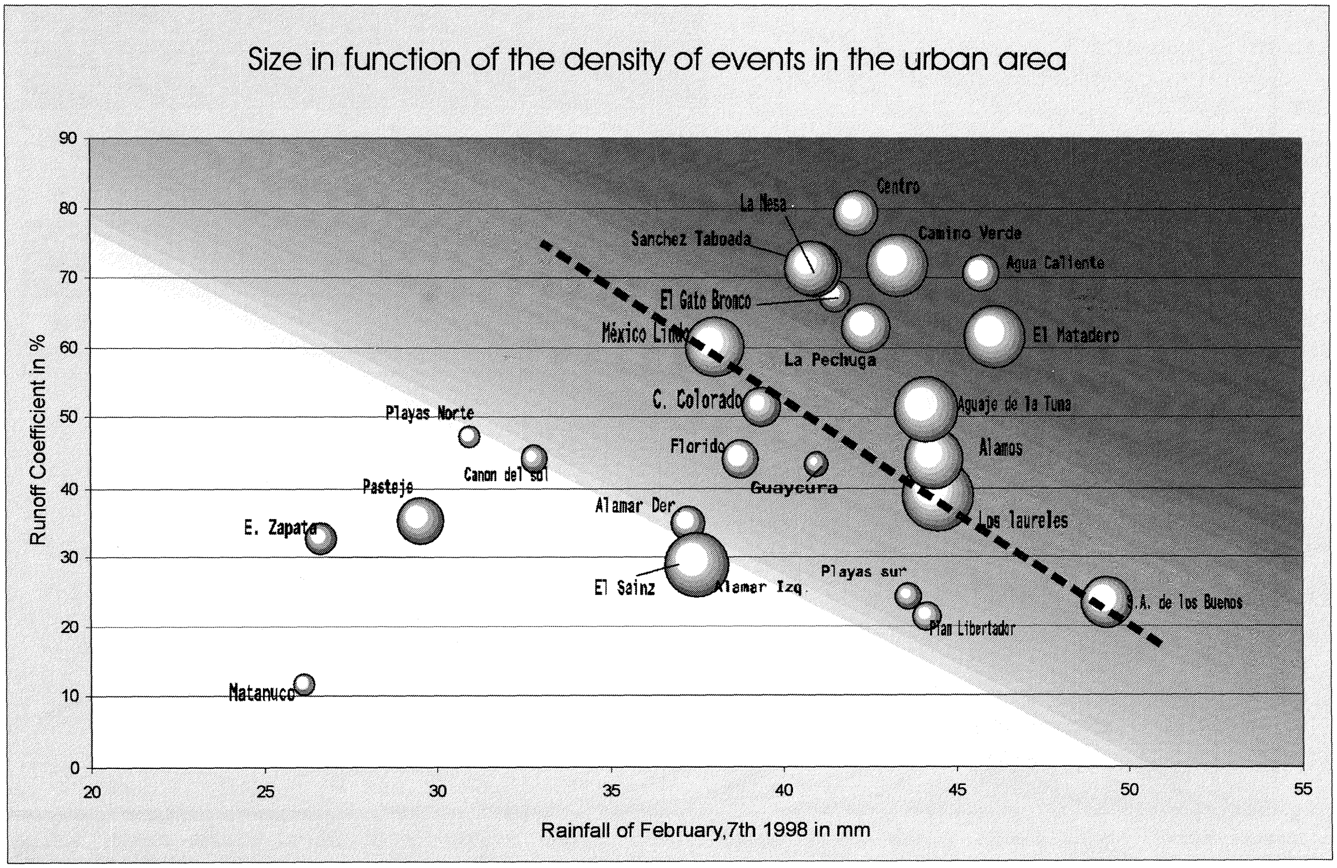


Fig. 11. Determination of thresholds of hazardous events.

left corner, those with the most, the most problematic, are in the uppper-right portion of the graph. The transition is abrupt and it can be drawn with a right line that joins México Lindo, Los Laureles, and San Antonio de los Buenos. Significant phenomena begin with a rainfall larger than 50 mm per day, in catchments with runoff coefficients of about 20 percent (San Antonio de Los Buenos). This threshold lowers to 45 mm per day with a coefficient of 40 percent (Los Laureles) and to 37 mm per day in a highly urbanized basin such as México Lindo, with a runoff coefficient of 60 percent. The numbers suggest an inadequate urbanization in these two last catchments.

5.2. A global vulnerability spatial assessment?

Three kinds of surface risks are related to rain events in Tijuana: flooding, water stagnation and gravity-induced morpho-dynamic processes on slopes. For each of these, we model the vulnerability of the urban areas and synthesize the potential risks on a map (Figure 12).

The areas exposed to flooding

Frequently, the areas with the greatest probability of flooding are located exclusively in the vicinity of the hydraulic channels, in depressed places with totally flat or smoothly undulating microtopography. This determination was done in two steps: First, a DEM (Digital Elevation Model) with a 30 meter resolution was superposed to the digital network of hydrographic channels. The selected logical function combines the calculation of the relative elevation between the closest hydrographic axis and each point of the reference mesh, according to its Euclidian distance in ArcView. Three categories were extracted: less than 1 meter, between 1 and 2 meters, and more than two meters. In a second process, this purely topographic result was combined with calculations of the runoff increase towards the lower section of the rivers (process Flow Accumulation of ArcView). Finally, a classification of the results differentiates two classes of potential flooding risks:

- Class 1 : areas with a lower risk of flooding.
- Class 2 : maximum risk of flood, in areas with the lowest relative elevation and greatest runoff coefficients,

The distribution of the urban zones with flooding vulnerability coincides almost perfectly with the events recorded during the last flooding episodes:

- Not surprisingly, most class 2 areas are located in the alluvial plains of the Tijuana River and its main tributaries (Alamar, Tecate) and extend to major portions of the coastal plain near the estuary.
- Risks levels 1 and 2 also occur in most of the tributaries in the unitary catchments (like Los Laureles, Matadero or Aguaje de la Tuna), but with a minimum extension due to the concrete channeling installed after January 1993.
- Extensive zones susceptible of flooding were also found in the plateau of Mesa de Otay. In this particular case, the results are correlated with the existence of very small relative altitude differences between the topographical surface and the river channels. Nonetheless, the flooding risk remains very low because of the small amounts of runoff.

Risks of water stagnation

Water stagnation occurs when, for topographic reasons, the water accumulated by precipitations cannot find a way out, and remains in these areas longer than usual. These zones can be assimilated to depressions and must contain a relatively impermeable substrate to resist normal infiltration. The stagnation can last for several days until the combination of draining and evaporation eliminates the water. The susceptibility to water stagnation was determined in a similar fashion to the flooding vulnerability. The same DEM with a 30 meter resolution provided the maximum unevenness inside of a square area of 90x90 meters. From these surface characteristics, two classes of risk, high and low, were defined.

The location of the zones with water stagnation vulnerability were also unsurprising. Near the Tijuana River, these areas are the same ones as the flooding zones and, of course, the risks related to floods become more severe. Outside the Tijuana River valley, water stagnation occurs in four zones of undulating surfaces or small:

- on Mesa de Otay, where the airport and the University are affected,
- on the eastern part of Playas de Tijuana, near the contact with the colluvio-alluvial fans at the piedmont of the eastern hills,
- in the similar topographic and geologic configuration on the eastern part of Rosarito,
- on several portions of the eastern city, where undulating topography in Ejido Matamoros or El Florido tends to retain water, and in several alluvial plains along the highway to Tecate.

Landslide risks

The slopes susceptible to outbreaks of gravity-sliding and slumps were determined with an aggregation method within a 250 meters pixel, similar in size to the blocks of the

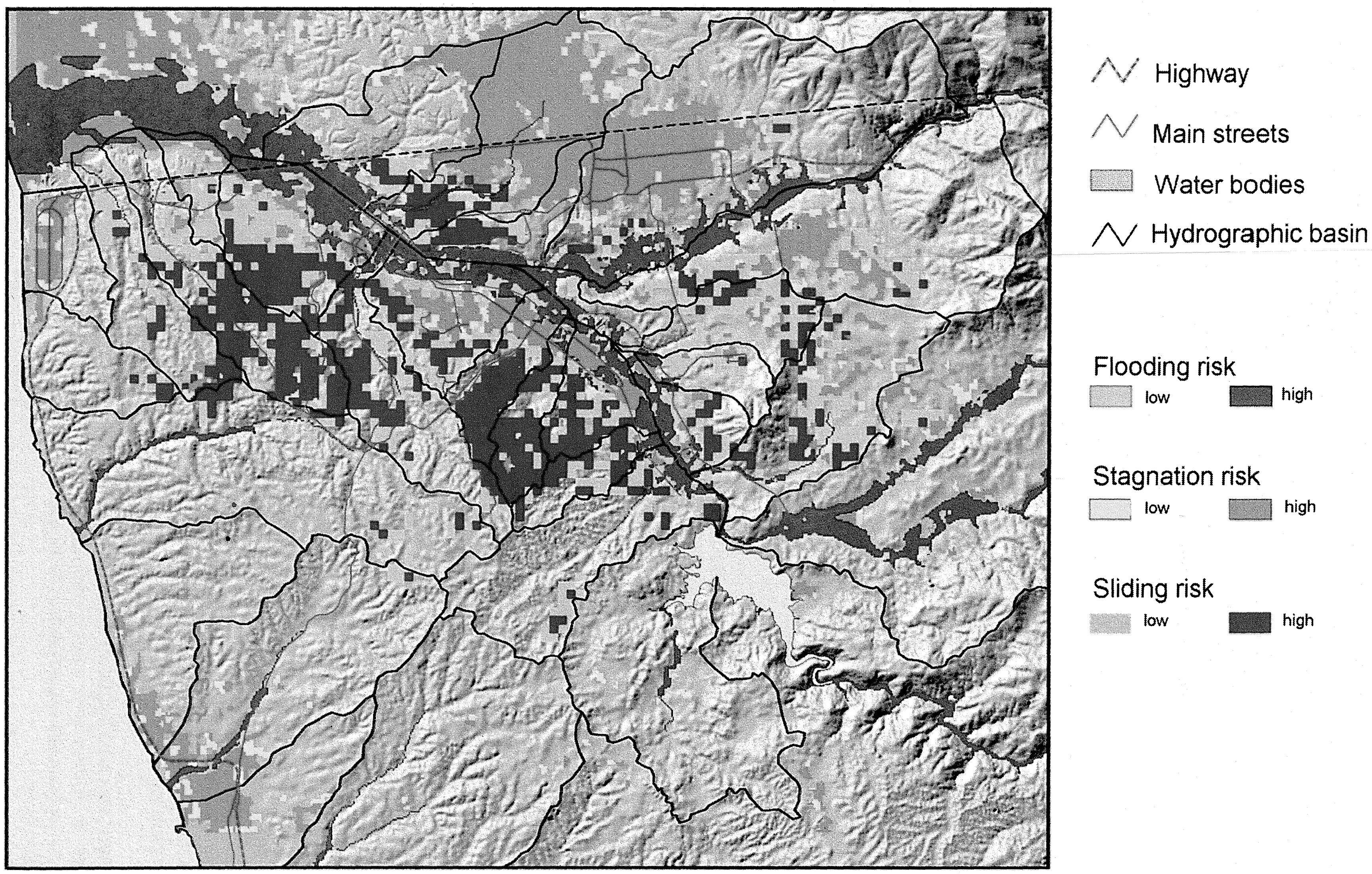


Fig. 12. Gradient of landslide risks from multivariate analysis.

city land registration, thus allowing a combination of physical and human information with a precise geographic location. Four parameters were coded and processed through a multiple regression analysis (LOGIT module in the ESTADISTICA software): the ground slope, the stability of the surface formations, the coefficient of land use-land cover, and the rainfall during the period of the study. The result is a hierarchy that can be interpreted, for each pixel, as the probability of a slope movement, and reported as a risk scale. Two periods of time were examined, one for the 8 - 12 of February, the second for the 13 - 22 of February; the maximum value obtained for each period is represented in a map, locating with sufficient precision the areas of potential problems.

Five main areas can be differentiated in the city:

- The Center-West of the city in the southwest hills of the Tijuana River valley, with a wide area that includes the two highest levels of risks; all are higly urbanized areas on steep hillsides around eroded canyons.
- The upstream half of Camino Verde, and some diffuse areas in Sánchez Taboada, La Mesa, México Lindo, and other basins where vast irregular settlements can be found above steep slopes.
- The north riverside of Zona del Río in the lower part of El Pasteze and La Pechuga basins, near the outlets of eroded ravines in Mesa de Otay.
- A wide distribution of isolated areas appears on the eastern periphery of the city, represented in the catchments with unfavorable conditions such as strong slopes, large amounts of dirt removal, barren soils, and high rainfall: Gato Bronco, El Florido, Cerro Colorado and Guaycura.
- Large areas exist within the city that have an acceptable level of risk, with few events recorded. Included here are Mesa de Otay, the eastern extensions of Playas de Tijuana, and some urbanized sections in the upper parts of Aguaje de la Tuna or El Sainz and, in some degree, in Zona del Río.

6. CONCLUSIONS

This study was designed to be a reference document, made available to the community, that would support the environmental decision-making process and the mitigation of natural risks. The survey was integrated with five operations, each published separately in technical and thematic manuals that include the basic and processed data. The results confirm the severity of the problems that the city of Tijuana faces when almost all the urban area is exposed, at one level or another, to rain-related risks.

A risk classification for all the elements of the watershed was carried out and a hierarchical list established of possible actions and priority interventions following a degree of the estimated danger. This should serve as a basis for a risk-reduction program, which is urgently needed by the city of Tijuana as the urban expansion of the city during the next twenty years should not take place without the sufficient planning.

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