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ORIGINAL ARTICLE

# Flood hazard assessment of Atrato River in Colombia

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**Abstract** The flood hazard caused by Atrato River in Quibdó, northwest of Colombia is assessed using statistical modeling techniques (Gumbel and GRADEX), hydraulic modeling with HEC-RAS and the Geographic Information Systems (GIS). Three flood hazard maps for return periods of 10, 20 and 50 years are generated. The flood hazard modeling reveals that the flooded zone is more significant out of the left (West) bank than out of the right (East) bank of Atrato River. For the three return periods the maximum depth of water reached by the river and extent of flooding are estimated. Sensitivity analysis on roughness coefficient and peak discharge is performed. For 50 year return period ($Q = 3054\ m^3/s$), water depth on the left and right bank of Atrato River is 3.7 m and 3.1 m, respectively. This information is useful in defining the minimum height of flood protection structures such as dikes to protect the area from flooding. The results can be useful for evacuation planning, estimation of damages and post flood recovery efforts.

**Keywords** Flood modeling · GIS · Gumbel · GRADEX · Flood hazard · Flood map · Atrato River · Quibdó · Colombia

## Introduction

Floods are the most common natural disasters that affect societies around the world. Jonkman (2005) analyzed the Emergency Events Database-EM-DAT maintained by the Centre for Research on the Epidemiology of Disasters in Brussels (CRED) and found that in the last decade of the 20th century floods killed about 100,000 and affected over 1.4 billion

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people. Dilley *et al.* (2005) estimated that more than one-third of the world's land area is flood prone affecting some 82 percent of the world's population. UNDP (2004) observed that about 196 million people in more than 90 countries are exposed to catastrophic flooding, and that some 170,000 deaths were associated with floods worldwide between 1980 and 2000. Those figures show that flooding is a major concern in many regions of the world. In Europe and especially in Mediterranean Region floods are the major natural hazards. During the past two decades, several extreme floods have occurred in central European rivers including the Rhine, Danube, Odra, and Wisla. One such disastrous flood occurred in the Elbe River basin and parts of the Danube basin in August 2002 (Becker and Grunewald, 2003). Rough cost estimates for the Elbe 2002 flood alone are approximately $3 billion in the Czech Republic and more than $9 billion in Germany. In USA, for example, in a period of 6 years (1989–1994) 80% of declared federal disasters were related to flooding; floods themselves average four billion dollars annually in property damages alone (Wardswoth, 1999). Losses from flood hazards in the United States are not only very large, on average, $115 million per week, but they have also been increasing dramatically (Congressional Natural Hazards Caucus Work Group, 2001). Flood damages in Canada are also on the rise (Ahmad and Simonovic, 2001, 2006; Simonovic and Ahmad, 2005).

In South America, concern over flooding has grown rapidly in recent years and has resulted in significant efforts to produce new information and studies of flooding patterns at national as well as transnational levels. Accumulated losses including investment, operation, and maintenance due to South American floods in the period 1995 to 2004 were of US$25 billion, (NIBH/SHS/EESC/USP, 2004). Wolfgang and Karin (1993) in a general review of tropical South American floodplains estimated the areal extent of different types of floodplains in this region. Hamilton *et al.* (2002) synthesized results of various works on the regional inundation patterns among the major floodplains of South America. They also analyzed the spatial as well as temporal variability in inundation patterns in the two largest South American flood plains (Hamilton *et al.*, 2004). Despite the progress in flood modeling research for flood hazard assessment, flooding continues to cause havoc in many areas of South America, Colombia is no exception. The occurrence of climate-related hazards has always been a serious threat for Colombian population. A recent and very severe flood, caused by a continuous and sustained above normal season of precipitation in the eastern, northern and western regions of Colombia, occurred in October and November of 2004, resulting in an emergency being declared in approximately one third of the country.

Colombia is divided into 32 States called departments and one Capital District. The Chocó department situated in the north-west corner of Colombia, is exposed to numerous natural hazards such as earthquakes, coastal erosion, landslides, storms, floods, and avalanches. Floods constitute the most prevalent natural disaster in Chocó department (Mosquera-Machado, 2002). Of the 287 natural disasters registered in the department between 1970 and 2000, more than three-fourth (76%) were caused by floods. The damages resulting from floods have the largest economic, social, and environmental consequences across the department and especially in Quibdó, the capital of the state.

In Colombia, like many other developing countries, field data defining the extent, timing, and depth of flooding are generally limited and are rarely available for large flood events. This makes flood modeling a challenging task. Since the blueprint paper by Freeze and Harlan (1969), flood modeling has been developing rapidly and as a consequence flood hazard assessment has considerably improved in recent years, especially due to the use of geographic information systems (GIS). Recent work in the area of flood modeling has focused on developing more efficient tools for GIS analysis. Robayo *et al.* (2004) developed a new Map-to-Map tool that concocts the Next Generation Radar-NEXRAD precipitation time series with GIS applications and hydrological modeling to produce a floodplain map. Remote sensing has also been acknowledged as a very useful tool in mapping flood extent (Horritt *et al.*, 2001) and hence for validating numerical inundation models. Despite the availability of sophisticated tools and techniques through GIS and remote sensing, still much remains to be understood about the relationship between runoff and flood extent and depth.

Several studies have been carried out in regional universities and institutions in Colombia on flood modeling (i.e. Cardona and Londoño, 1991; Franco and Perez, 1995; Acosta and Ruiz, 1997). An assessment study of inundation of Magdalena basin was carried out by National Institute of Hydrology, Meteorology and Environmental Studies-IDEAM in 1997. Most of these studies, however, are limited to the calculation of maximum discharges associated to different return periods and to the extent of the area flooded in regions other than Chocó department. No flood studies have been carried out in Chocó department so far. An important prerequisite for developing management strategies for the mitigation of extreme flood events is to identify areas of potentially high risk to such events, thus accurate information on the extent of floods is essential for flood monitoring, and relief (Smith, 1997).

This study aims at assessing the flood risk caused by Atrato River in Quibdó, the capital of Chocó department, located in north west of Colombia. We present an approach combining statistical techniques, hydraulic modeling and GIS to assess the risk of flooding in Atrato River in Quibdó. We estimate the depth and extent of flooding in Quibdó for floods of 10, 20 and 50 years of return periods.

The remainder of this paper is organized as follows. First the study area is described. That is followed by details on the method used to model flood hazard. Details on data sets used in this research are provided, statistical modeling techniques used to estimate flood discharge are described, and details on hydraulic modeling are provided. A rigorous sensitivity analysis of roughness coefficient and peak discharge is reported. This is followed by results and discussion of findings. The paper concludes with comments on potential applications of research findings.

## Study area

The focus of this study is the Atrato River in Quibdó. The Atrato River is 750 km long and is the fastest flowing river in the world, discharging 4,900 $m^3/s$ of water into the Caribbean (Government of Colombia, 1993).

Quibdó is situated at 5°41′13″ Latitude North and 76°39′40″ Longitude West with an area of 3,337 $km^2$ (Figure 1). The altitude of study area ranges from 23 to 75 m above mean sea level. It lies in the multi-hazard prone (earthquake, landslide, coastal erosion and floods) and economically backward Chocó department on the pacific region of Colombia. Chocó department is composed of 31 municipalities, and Quibdó is the capital. Quibdó is a city seriously affected by natural hazards, especially extreme weather and climate events, among which flood disaster causes the most serious damages and losses (Mosquera-Machado, 2002). Quibdó not only has the highest incidences of disaster but also the variety of associated hazards, including floods, earthquakes, landslides, strong winds, and storms (in descending order, respectively). Quibdó ranks first by diversity and recurrence of disasters during the past three decades, with 85 disasters of five different types (Mosquera-Machado, 2006). The estimated direct economic losses of disasters reached US$1.6 billion (adjusted price) for 1970–2000.

Tectonics and geological data of northwestern region of Colombia are more abundant than those of Quibdó (i.e. Nygren, 1950; Case *et al.*, 1971; Macia, 1985). The geological

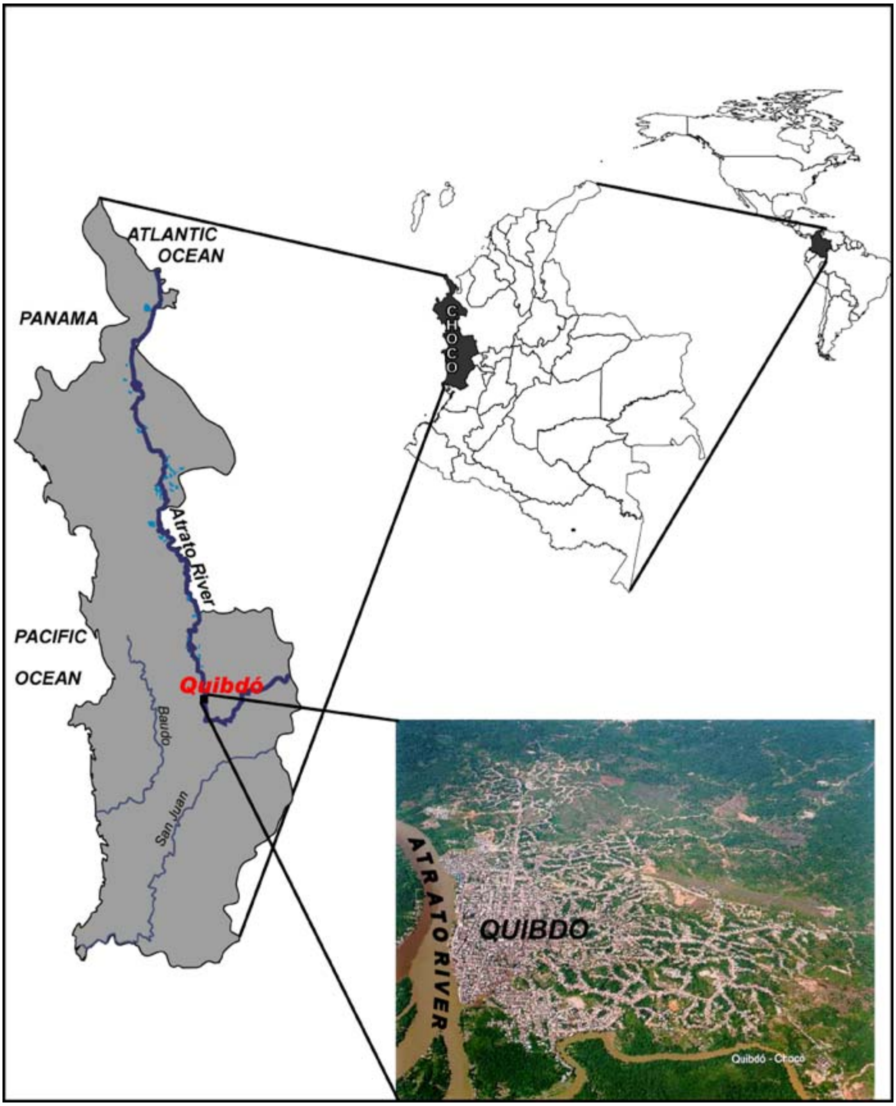


**Fig. 1** Geographic location of study area

map of Chocó department was done by Cossio (1994) with adaptation from Duque-Caro (1990). In Quibdó, one can delimit two zones geologically different: in the west and limited by Atrato, is the low zone made up of recent alluvial deposits coming from Atrato and the remainder of its tributaries. On east side of Quibdó, one finds the higher zone made by slopes formed primarily of river-derived pelites, sandstones and marine conglomerates. Structurally, this zone is marked by alignments with north-south orientation, associated with erosive processes, the abrupt changes in the drainage and the deep incisions in the river beds.

The municipality of Quibdó is made up of an urban zone with 80,000 inhabitants and a rural zone with 34,300 inhabitants. (DANE, 1993) Quibdó has grown exponentially over the last decades. The urban development is characterized by the lack of planning at the point that there are houses built directly in the riverbed.

The highest annual rainfall in the Americas, and among the highest in the world, is observed in the Chocó department, on the Pacific coastal plain west of the Andes (Eslava, 1992, 1994; Horel and Cornejo-Garrido, 1986; Figueroa and Nobre, 1990; Mesa *et al.*, 1997; Poveda and Mesa, 2000). In Quibdó precipitation is very intense with an annual average value of 8700 mm. Maximum daily rainfall in Quibdó, extracted from IDEAM data for Atrato sub-basin ranges between 35 mm in January and 301 mm in July. The average temperature is 27°C and the average relative humidity is 98%.

The hydrographic network of Quibdó is formed by Atrato River and its tributaries Cabi, La Yesca, Guayabal, Quito, La Platina, and Tutunendo. The section of the Atrato River floodplain chosen for investigation lies adjacent to the urban part of Quibdó. The Atrato River in this reach is a 250–500 meter-wide meandering alluvial channel which occupies a 2–3.5 km-wide valley. The upper Atrato River catchment has a maximum elevation of 3,300 m at the El Carmen watershed in the northeast.

## Method

For this work we developed a method based on the use of statistical techniques of Gumbel and GRADEX, hydraulic modeling (using HEC-RAS), and the Geographic Information Systems (GIS). The proposed method to evaluate the flood risk in a river flood plain involves several steps: (1) Rainfall data, stream flow data, topographic data as well as geological and land used data were collected, stored and preprocessed in Excel and Dbase. (2) The data digitalization was carried out in IDRISI, Arc/Info, and Arc/View. (3) Flood frequency analysis was done by selecting maximum daily precipitation in Quibdó and monthly and annual maximum gauge levels at Atrato gauge site. Two methods of statistical distribution i.e., Gumbel's extreme value distribution and GRADEX are employed by selecting peak gauge level data for 24 years (1970–1994) at Quibdó. (4) The hydraulic simulation of Atrato River's floods to predict water level in the river and floodplains is done with HEC-RAS. (5) The hydraulic simulation is validated through the calibration of manning roughness coefficient using the observed water levels during the great flood of Chocó department on October 17th, 1994. (6) Sensitivity analysis is carried out on roughness coefficient and peak discharge. (7) The HEC-RAS results are processed using GIS tools (IDRISI and Arc-Info) to produce the flood hazard maps of Atrato River in Quibdó. The flow chart of the method is presented in Figure 2.

## Data collection and preprocessing

Rivers situated deep inside tropical rain forests are often poorly gauged, and data on extreme flows are rare. Even when stations are gauged, it is quite common that >40% of the record is missing; the rivers of the northwestern of Colombia are no exception. There are twenty three hydro-meteorological stations in Chocó Department, 11 are in the Atrato River and the remaining 12 are located on the tributaries. The hydrological stations measure water level, from which the river discharges are computed. The meteorological stations measure precipitations and in some case the extreme temperatures. Within a radius of twelve kilometers from the center of the watershed there is a network of five rain gauges reporting hourly rain accumulations, two of which are closer to the watershed, providing representative estimates of the basin-averaged hourly rainfall rates. The two stations used in his study have an observational

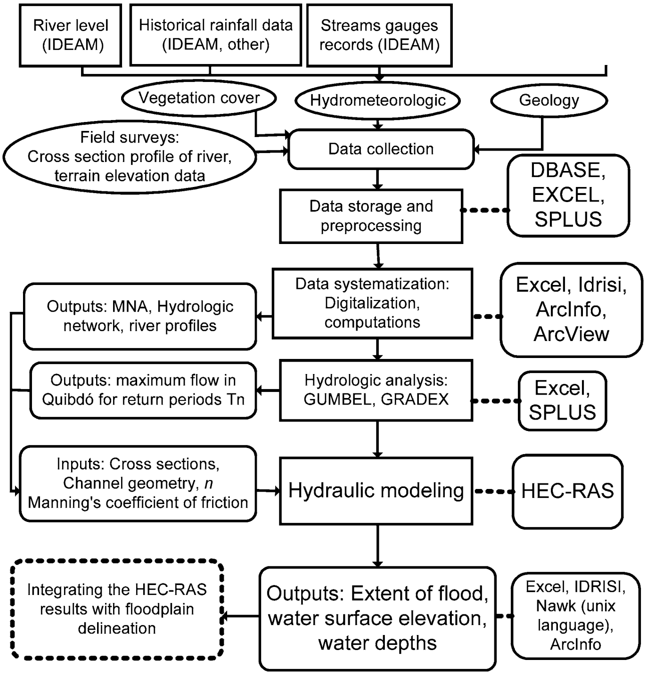


**Fig. 2** Flow chart for hydraulic analysis of Atrato River

period of more than 18 years. We obtained precipitation and water data from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) for Atrato River in Quibdó.

The sources of information used for this flood risk assessment study include aerial photographs, topographic maps, geological maps, soils maps (IGAC, 1977), and stream flow and precipitation records. The spatial topographic data was obtained from a wide variety of sources such as the Instituto Geografico Agustin Codazzi (IGAC) in the form of paper maps, river surveys and field observations. Procedure of digitization was adopted to convert these maps into digital form. Digital data was stored using the Toscanel module of IDRISI (Eastman, 1997), in the form of regular or random data points, isolines and polygons.

## Generation of digital elevation model of Quibdó

The Digital Elevation Model (DEM) was developed for Quibdó by digitization of the contour lines and point elevations from the IGAC 1:5000 geographic quadrangles, and the 1:2000 plan of Quibdó city. Additional points were obtained using a GPS in field survey done specifically for this research. The Atrato river cross sections and point elevation values for benchmarks were digitized to provide additional elevation information for creation of the DEM. The coverages created for interpolation in Arc Info where: (i) arc coverage of contours lines with an equidistance of 10 m, (ii) the hydrologic network of Quibdó (composed of Atrato river and its tributaries), (iii) survey points of Quibdó, (iv) Atrato river's cross-sections 20–100 m apart from field survey or from topographical maps of scale 1:2000, (v) profiles of Atrato River from the National Institute of fluvial transportation.

First only the contours lines were interpolated in ILWIS obtaining a DEM with visual errors and artefacts. Next the interpolation was done using the TOPOGRID Module of ArcInfo, that allows the combination of different types of coverages, including single rivers profiles, hydrologic networks, contours and points. The resulting DEM of Quibdó has a grid resolution of 20 m with a contour interval of 5 m. The DEM has a square grid array and is thus computationally efficient. To estimate the accuracy the DEM was field checked using a GPS at 80 points; it was found that a vertical error of 1.5 cm and horizontal error of 0.25 m exists.

## Hydrologic frequency analysis

The frequency analysis is used to relate the magnitude of extreme events to their exceedance probability though the use of probability distribution. The return period of any event in observation is the inverse of its exceedance probability. Since prediction of large floods requires knowledge of the underlying distribution, major portion of the work was devoted to statistical modeling of extreme values using some well-established theories. The statistical distribution of Gumbel is a frequential model widely used in hydrology, to model extreme events, rains in particular. Gumbel (1958) postulates that the exponential double law of Gumbel is the limiting form of the distribution of the maximum value of a sample of $n$ values. The annual maximum of a variable being regarded as the maximum of 365 daily values; this law must thus be able to describe the series of maximum annual. The function of distribution of the law of Gumbel $F(x)$ is expressed in the following way:

$$F(x) = \exp\left(-\exp\left(-\frac{x-a}{b}\right)\right) \tag{1}$$

where $a$ is the location parameter and $b$ is the parameter of scale.

Defining the reduced variable of Gumbel as

$$u = \frac{x-a}{b} \tag{2}$$

Then the Gumbel distribution may be writen as:

$$F(x) = \exp(-\exp(-u)) \tag{3}$$

and

$$u = -\ln(-\ln F(x)) \tag{4}$$

The advantage of using the reduced variable of Gumbel $u$ is the linearization of the expression of a quintile. The calculation of the value of a quintile $x_q$ can be done either by direct reading on the graph or by using the equation of distribution

$$x_q = a + bu_q \tag{5}$$

Figure 3 shows the Gumbel distribution of Atrato River in Quibdó with the data series of monthly maximum discharges for the period 1974–1994.

The computation of design flow for long return period in Quibdó was done using the probabilistic GRADEX method, which extrapolates discharge distributions according to the rainfall distributions. The GRADEX method was developed in France by Guillot and Duband

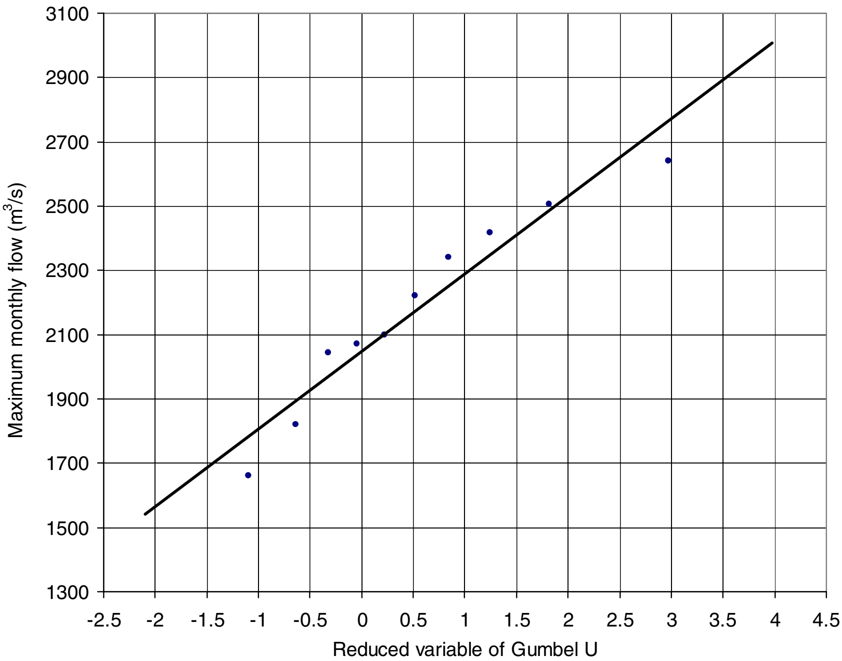


**Fig. 3** Gumbel analysis for Atrato River in Quibdó (1984–1994)

in 1967 for extreme flood estimation in catchments up to 5000 square kilometers, and it is widely used in Europe and Canada (i.e Garçon, 1993; Bontron *et al.*, 1999; Ouarda *et al.*, 1999; Merz *et al.*, 1999; Blöschl *et al.*, 2000; Mic, 2002). The GRADEX represents a simplified rainfall-runoff model which provides estimates of flood magnitudes of given probabilities and is based on rainfall data which often cover longer periods and are more reliable than flow data. It is based on the hypotheses (Guillot and Duband, 1967; Guillot, 1973; Duband and Garros, 1994) that beyond a given rainfall threshold known as the pivot point, all water is transformed into runoff, and that a rainfall event of a given duration generates runoff for the same length of time. These hypotheses are equivalent to assuming that, beyond the pivot point, the rainfall-runoff relationship is linear and that the precipitation and runoff probability curves are parallel on a Gumbel plot. This definition is equivalent to taking the slope of the line passing through the points corresponding to the given return period on a Gumbel plot. For Quibdó's station we evaluated eleven GRADEX values, i.e., one for each month (except August for which data was missing) using data from 1974–1994. Then we obtain the GRADEX values and estimated extreme flow value for different return periods. One example of the frequency analysis for Quibdó using the GRADEX method is illustrated in Figure 4. The estimated discharges for 10, 20 and 50 years of return period using Gumbel and Gradex method are reported in Table 1. The last row in the table shows the selected values of discharges used for hydraulic modeling.

## Hydraulic analysis

We developed a comprehensive GIS database to support this research, as we needed to prepare the geometric parameters and input for the hydraulic analysis. All data were either input

**Table 1** Estimated discharges of Atrato River in Quibdó using Gumbel and GRADEX methods

| Month | $Q$ for $T = 10$ years ($m^3$/s) | | $Q$ for $T = 20$ years ($m^3$/s) | | $Q$ for $T = 50$ years ($m^3$/s) | |
|---|---|---|---|---|---|---|
| | Gumbel | Gradex | Gumbel | Gradex | Gumbel | Gradex |
| January | 2559.3 | 2575.5 | 2761.3 | 2825.3 | 3002.1 | 3042.1 |
| February | 2019.3 | 2032.3 | 2148.3 | 2252.4 | 2300.1 | 2358.1 |
| March | 2457.5 | 2457.1 | 2638.5 | 2578.1 | 2888.5 | 2912.4 |
| April | 2520.2 | 2498.2 | 2732.3 | 2761.1 | 3009.1 | 3028.1 |
| May | 2449 | 2461 | 2569.6 | 2591.6 | 2723.1 | 2741.3 |
| June | 2666.5 | 2675.5 | 2867.5 | 2867.5 | 3027.1 | 3053.6 |
| July | 2303.3 | 2320.3 | 2450 | 2460.4 | 2633.1 | 2644.2 |
| August | 2654.9 | | 2875.9 | | 3036.1 | |
| September | 2514.2 | 2544.1 | 2686.5 | 2697.3 | 2921.5 | 2930.6 |
| October | 2589.6 | 2599.6 | 2767.6 | 2777.6 | 2990.1 | 2990.1 |
| November | 2544.7 | 2562.8 | 2692 | 2720.1 | 2981.5 | 2908.5 |
| December | 2349.4 | 2289.3 | 2485 | 2425.2 | 2669.3 | 2718.3 |
| Discharges $Q$ used for flood simulation | 2676 | | 2868 | | 3054 | |

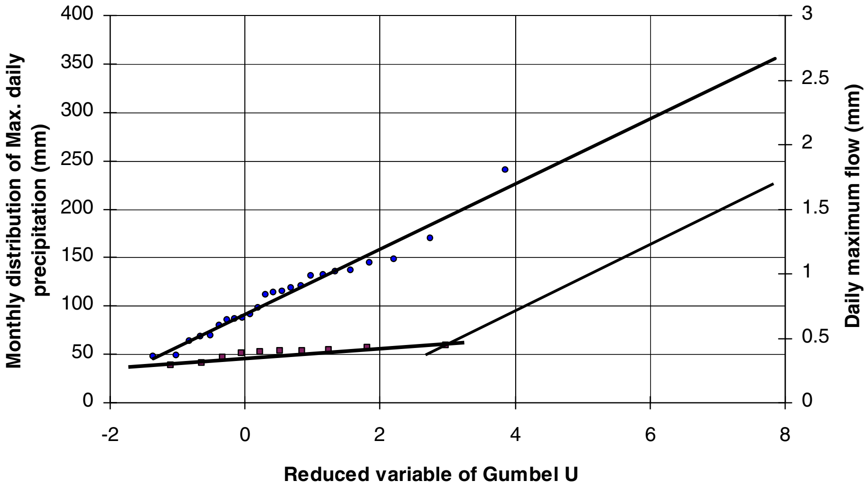


**Fig. 4** GRADEX analysis for Atrato River in Quibdó (1970–1994)

or derived within IDRISI (a raster-based GIS and image processing software) or Arc/Info (a vector-based GIS). The base variables included elevation contours, elevation points, hydrographic network, soils and watersheds.

The Atrato river hydraulic modeling was done using the HEC-RAS, River Analysis System (USACE, 1998). The HEC-RAS computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction using Manning's Equation (6) and contraction/expansion (coefficient multiplied by the change in velocity head).

$$Q = \frac{k}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (6)$$

where $Q$ is the channel discharge, in cubic meter per second; $A$ is the cross-sectional area of channel flow, in square meter; $R$ is the hydraulic radius of flow cross section in meter; $S$ is the slope of the energy gradient; $n$ is the Manning's coefficient of channel roughness; and $k$ is the coefficient for unit type, $k = 1.486$ for English units and $k = 1.0$ for SI units.

As model inputs, HEC-RAS requires the river channel geometry, the flood discharge information $Q$ for each cross section, the channel cross sections, including left and right bank locations; and roughness coefficients (Manning's $n$). The geometric data was imported into HEC-RAS that included the stream network and cross-sectional geometry. Station-elevation data, bank stations, downstream reach lengths, and levee information were imported for each cross section. For the flood simulation the discharge used were the largest calculated for the three given return periods. The roughness coefficients, which represent the surface's resistance to flow and are integral parameters for calculating water depth, were initially estimated using the Chow classification. Chow (1959) provides the most thorough set of roughness values for various surface materials to date, including descriptions and photographs to help in estimation of suitable values. A complete overview of methods for establishing roughness values is given in Sellin *et al.* (2003). The resulting Manning coefficient was calibrated using the water extend and depths from the flood event of October 1994 (a 50 years flood). The Manning's coefficients used for different zones of the Atrato river varies between 0.038 and 0.068. Flood inundation results were derived separately for each cross section in the main channel. A total of 140 cross sections were processed over the channel.

## Model calibration

It is generally accepted that the reliability of application of any conceptual and even physically based model depends much on the success of the calibration process used to identify values for the model parameters (Seibert, 1997). Model parameters can largely be divided into two categories (Melching, 1995): (i) parameters that can be directly inferred from observation, such as area, extent, depth, volume etc., and (ii) parameters that cannot be directly observed at the model scale and will need to be estimated, such as roughness. Manning roughness coefficient $n$, together with the channel geometry is considered to have the most important impact on predicting inundation extent and flow characteristics. Therefore, the focus of this section is the calibration of the roughness coefficients.

Most of the methods from literature for estimating roughness values are useful in establishing the range of roughness values for a river reach. Calibrated roughness values are, however, effective at the reach scale (Beven and Carling, 1992). We started with roughness value estimates given in Chow (1959). We used 1994 flood for calibration of Manning's $n$. During the October 1994 flood, Quibdó City situated in the floodplains of Atrato reach suffered extensive inundation. An exceptionally complete dataset of this event was collected by the first author (at that time the technical coordinator of Regional Disaster Committee, CRED-Chocó) with the assistance of the Colombian Army and Civil Defense of Chocó. The collected data included the extent of flooding, as well as 15 points of depths measurement, giving an indication of the distributed flood depths in the floodplain. An example of the water level and depth data collected is summarized Table 2. Where R Sta. is the number of river cross-section or station measured, W.S. Elev. is the water elevation, W. Ext. L is the extent of flood water in the left bank, and W. Ext. R is the extent of flood in the right bank of the river.

Calibration is an inverse problem associated with identification, and is used to determine unknown constants or parameters in a model. Calibrating the Atrato River model roughness values involved running the hydraulic model several times and changing the Manning roughness coefficients, first estimated from Chow tables, until the best fit between the simulated

**Table 2** Observed data of great flood of Chocó in October 1994

| R Sta | W. S. Elev (m) | W Ext L (m) | W Ext R (m) |
|---|---|---|---|
| 129 | 30.70 | 1787.17 | 306.11 |
| 127 | 30.63 | 1375.50 | 230.67 |
| 126 | 30.61 | 1287.39 | 291.27 |
| 122 | 30.46 | 979.14 | 272.34 |
| 121 | 30.44 | 895.03 | 451.91 |
| 115 | 30.23 | 1139.31 | 109.29 |
| 114 | 30.18 | 834.02 | 221.95 |
| 113 | 30.18 | 1246.69 | 624.16 |
| 110 | 30.05 | 978.02 | 299.24 |
| 107 | 29.96 | 1448.23 | 334.78 |
| 106 | 29.94 | 1349.30 | 295.44 |
| 105 | 29.92 | 1473.70 | 290.08 |

**Table 3** Calibration and sensitivity analysis for Manning's roughness coefficient using $Q = 3054\,m^3/s$ (Return Period: 50 year)

| R Sta | Man. L (n) | Man. Ch. (n) | Man. R (n) | W. S. Elev (m) | W Ext L (m) | W Ext R (m) |
|---|---|---|---|---|---|---|
| 129 | 0.052 | 0.06 | 0.038 | 30.47 | 1467.11 | 274.52 |
| 129 | 0.048 | 0.064 | 0.038 | 30.52 | 1541.62 | 278.44 |
| 129 | 0.048 | 0.06 | 0.042 | 30.45 | 1431.5 | 273.64 |
| 129 | 0.048 | 0.06 | 0.038 | 30.43 | 1406.85 | 273.04 |
| 129 | 0.048 | 0.06 | 0.034 | 30.41 | 1374.84 | 272.26 |
| 129 | 0.048 | 0.056 | 0.038 | 30.33 | 1248.07 | 269.17 |
| 129 | 0.044 | 0.06 | 0.038 | 30.39 | 1341.81 | 271.46 |
| 129 | 0.56 | 0.68 | 0.38 | 30.7 | 1787.17 | 306.11 |
| Manning's *n* derived from Calibration | | | | 0.056 | 0.068 | 0.038 |
| Manning's *n estimated from Chow* | | | | 0.048 | 0.06 | 0.038 |

and observed water level and water extend is found. No adjustments in the values for expansion/contraction coefficients were made. The river cross sections were divided into three zones for calibration: Left bank, main channel and right bank. A summary of trials for calibration and sensitivity analysis is presented in Table 3. In this table Man. L is the Manning coefficient of the left bank, Man. Ch. is the Manning coefficient of the main channel, Man. R is the Manning's coefficient of the right bank, W. S. Elev is the elevation of water, W Ext L and W Ext R is the extent of flood in the left and right bank, respectively. After several dozen trials the best-fit between simulated and observed water levels was achieved using the Manning values of 0.056 for the left bank, 0.063 for the main channel and 0.038 for the right bank.

## Sensitivity analysis

Sensitivity analysis is a widely used tool in modeling to determine how the variation in model performance can be apportioned to different parameters (Crosetto *et al.*, 2000). In this study sensitivity analysis is used to estimate how changes in Manning's roughness coefficient and peak discharge will impact the flood depth and flood extent, two most important parameters to develop a flood hazard map. First, we performed sensitivity analysis on Manning's roughness coefficient. Each channel cross section in the model was divided into three segments: left bank, main channel, and right bank. The *n* value for the floodplains on left and right bank and

**Table 4** Results of sensitivity analysis on peak flow

| $Q$ increment (%) | $Q$ Total ($m^3$/s) | W. S. Elev (m) | W. Extent L (m) | W. Extent R (m) | W S Elev increment (m) | W Extent L increment m (%) | W Extent R increment m (%) |
|---|---|---|---|---|---|---|---|
| 0 | 3054 | 30.70 | 1787.17 | 306.11 | 0 | 0 (0) | 0 (0) |
| 5 | 3206.7 | 30.79 | 1944.5 | 323.84 | 0.1 | 157.32 (8.8) | 17.13 (5.8) |
| 10 | 3359.4 | 30.89 | 2031.03 | 341.03 | 0.2 | 243.85 (13.6) | 34.92 (11.4) |
| 15 | 3512.1 | 30.98 | 2047.45 | 357.45 | 0.29 | 260.27 (14.5) | 51.26 (16.8) |
| 25 | 3817.5 | 31.16 | 2064.57 | 374.57 | 0.46 | 277.39 (15.5) | 68.46 (22.4) |
| −25 | 2290.5 | 30.09 | 932.37 | 259.47 | −0.6 | 854.81 (−47.8) | 46.64 (−15.2) |

main channel were then changed systematically and the corresponding change in the flood depth and extent was analyzed. Results are reported in Table 3.

Sensitivity analysis was also performed on peak discharge. We used 50 year return period event ($Q = 3054\,m^3/s$) for the analysis. We varied the peak discharge up to 25% (increased and decreased) at an increment of 5%. We made comparisons between observed water surface elevation and water extent on left and right bank at station 129. Results are reported in Table 4.

### HEC-RAS results post-processing

After executing the HEC-RAS model, the results are written to an output report using the "generate report" option in the HEC-RAS file menu. The resulting report is a text file that contains information describing cross sectional geometry, stream flow rates, and water-surface profiles. Several steps were needed to translate the outputs of the hydraulic modeling into a flood map (Figure 5): First the text output files were converted to Excel format. Second, the left and right distances calculated by the model in meter must be translated in *x, y* coordinates of the cross sections. Third, utilizing Nawk, a language of UNIX environment, a program was written to find the intersection of the distances with geographic coordinates of each cross section. Forth, the intersection points were imported to IDRISI where they were combined with the DEM to interpolate the contour line of the surface of inundation. Fifth, the interpolated contour lines were converted to flooded surface polygons in IDRISI (a polygon was created in IDRISI for each return period and exported to ARC/INFO). Sixth, from the polygons three masks were created with ARC/INFO. Seventh, the masks were overlay with the DEM of Quibdó and the city plan to obtain the flood hazard maps.

## Results

Four types of results were obtained in this analysis. First, the hydrologic frequency analysis using statistical techniques provides two sets of design flows for return periods of 10, 20 and 50 years. The design flood calculated with the Gumbel and Gradex approach are given in Table 1. An ascending tendency has been observed in the Gumbel probabilistic approach for the frequency volumes, and indicates statistic non-homogeneity of population from the flow sample. The non-homogeneity occurs because the urbanization effects on flood frequency distribution are neglected.

The GRADEX estimations of flood are larger than the flood estimates from Gumbel calculations. This is because the GRADEX method was originally developed for the estimates of extreme floods in Dams (Bouvard and Garros-Berthet, 1994) and it combines rainfall

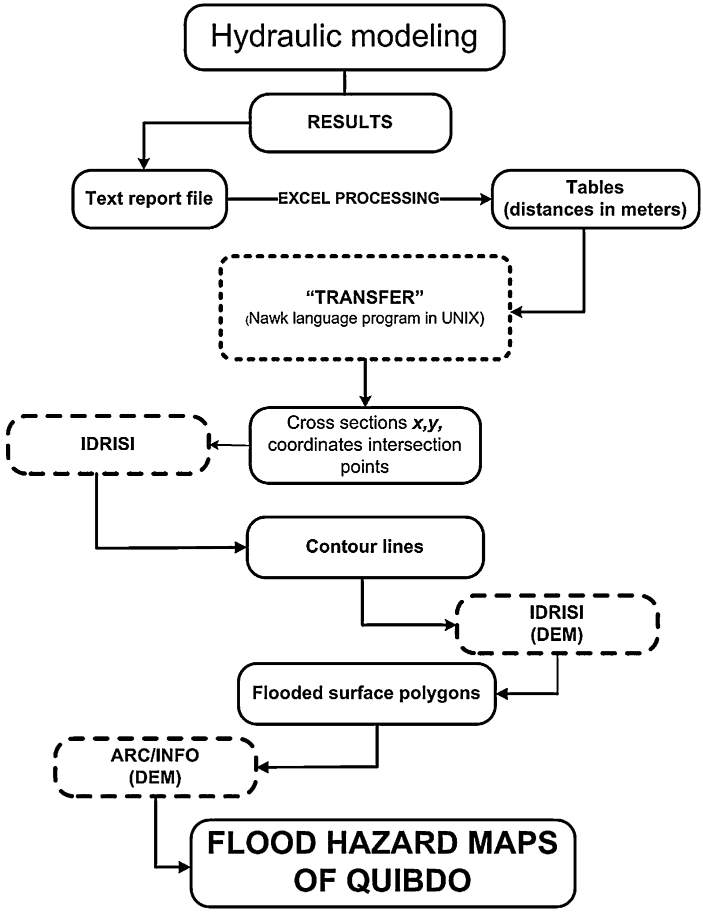


**Fig. 5** Flowchart for the generation of flood hazard map for Atrato River in Quibdó

and flood statistics. At the heart of the method is the assumption that the average maximum storage capacity is reached at a return period T. The storage capacity is the difference between catchment rainfall and runoff. From this assumption follows that, for rainy episodes greater than storage capacity, the catchment can be assumed to be completely saturated and consequently any additional rain that arrives to the river produces a corresponding increase in the runoff. This assumption is a weakness of the GRADEX method, because rainfall of a given probability does not necessarily cause a runoff of the same probability. Even if the GRADEX method tends to overestimate flood quintiles (discharge estimated and associate return period), the largest estimated flows for each return period were retained to guaranty that extreme conditions of flooding were taken into account during the hydraulic modeling with HEC-RAS.

Results of model sensitivity to changes in selected parameters are reported in Table 3. To estimate relative sensitivity of roughness coefficients (Manning's $n$) for main channel and right and left banks of floodplains we varied the Manning's $n$ above and below the computed values from Chow. We started with changing the roughness coefficients (Manning's $n$) for one segment (either main channel or left bank or right bank) while holding the $n$ for other

**Table 5** Results from HEC-RAS showing water depths and water surface elevations

| R Sta | Return Period T (years) | W S Elev (m) | W depth on right bank (m) | W depth on left bank (m) | W Ext L (m) | W Ext R (m) |
|---|---|---|---|---|---|---|
| 129 | 10 | 28.87 | 1.0 | 1.8 | 835.77 | 203.15 |
| 129 | 20 | 29.55 | 1.8 | 2.6 | 1235.26 | 285.02 |
| 129 | 50 | 30.70 | 3.1 | 3.7 | 1787.17 | 306.11 |

two segments of cross section constant. Corresponding water surface elevations in main channel and extent of flooding on both right and left bank are computed and compared with observed values for the flood of 1994. Results show that, for example, changing the roughness coefficient for main channel from 0.06 to 0.056 results in 10 cm reduction in water level and 158 m and 4 m decrease in water extent on left and right banks, respectively. Similarly, an increase in roughness coefficient for left bank from 0.048 to 0.052 results in 4 cm increase in water level and 60 m and 1.5 m increase in water extent on left and right banks, respectively. Comparison of observed and calculated water levels in Atrato river shows clear sensitivity to both main channel and floodplains roughness. Summarizing these results qualitatively, simulation results are most sensitive to the roughness coefficient in the main channel, followed by roughness coefficient of left bank and right bank, respectively. The last two rows in Table 3 give the roughness values of manning's *n* obtained through calibration and estimated using Chow's table.

With sensitivity analysis on peak discharge we found that both water surface elevation and extent of flood are sensitive to change in discharge, for example 10% and 25% increase in discharge results in 0.2 m and 0.46 meter increase in water surface elevation, respectively. Water extent is more sensitive to change in discharge for example, a 25% increase in discharge increases water extent by 277 m on left and 68 m on right bank, respectively. A 25% reduction in peak flow results in reduction of flood depth by 0.6 m and extent by 855 m on left and 47 m on right bank, respectively.

Table 5 shows an example of output parameters computed through hydraulic modeling with HEC-RAS for Atrato River in Quibdó. Where *R Sta* is the identification number of the cross section station of the channel, *W. S. Elev* is the height of the water calculated from the energy equation, *W* depth on right bank, and *W* depth on left bank are the water depth on the right and left bank respectively, *W. Ext L* is the boundary of flooded surface in the left bank of the river, and the *W. Ext R i*s the boundary of flooded surface in the right bank of the river.

The difference in the results calculated for the right and left bank of Atrato River in Quibdó can be attributed to the difference of altitudes in both sides of the river. The final output of the study consists of flood hazard maps of Quibdó. Three flood hazard maps were developed for Quibdó for three return periods of 10, 20 and 50 years. The hazard maps of Quibdó are illustrated in Figures 6a–c. The maps represent the digital elevation and plan map of the site with the flooding extent for a given return period. The limits of the area inundated by flood water as well as the flood extent and depth of flooding on each side of the city can readily be seen from these maps.

The flood hazard maps confirm the results in Table 5 illustrating the difference in the extent and depth of flooding on the right and left bank of the river. It can be noted that the flooded area becomes proportionately larger with increasing return period. The maps also show that the difference in altitudes separating the two banks of Atrato River in Quibdó results in an extension of the flooded area clearly more on the left than on the right for all three return periods.

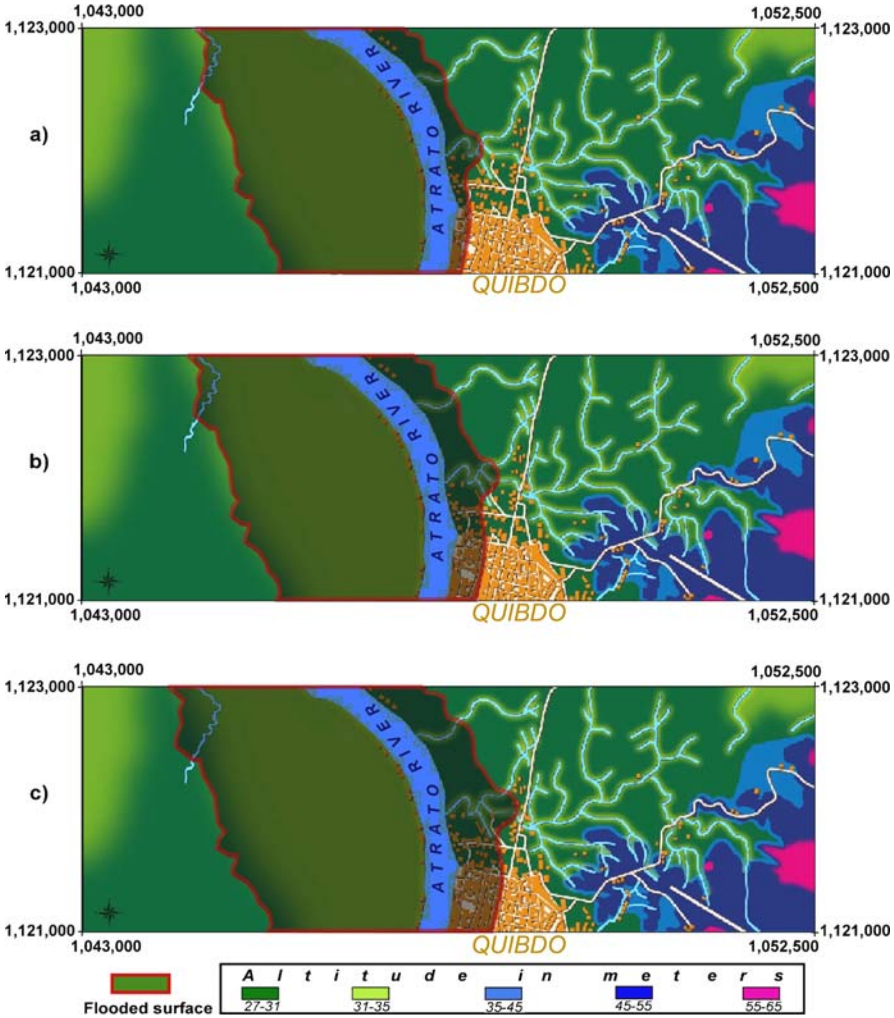


**Fig. 6a–c** Inundation maps for the 10, 20 and 50 year return period floods

## Discussion

Hazard mapping and risk assessment forms the foundation of the risk management decision-making process by providing information essential to understanding the nature and characteristics of the community's risk. The first step in risk assessment for floods is the development of hazard maps. These maps are useful for operational risk management and for disaster mitigation.

The problem of assessing the risk of flooding is not always a simple one. In flood-prone areas estimation of both the depth of water and the extent of the flooded area are essential. The approach presented in this study deals with estimation of both, depth and extent of flooding and follows, as much as possible, a physically based representation of the hydrological phenomena involved, so as to overcome the lack of available information, a situation all too frequently encountered in practice. In particular, the use of the GRADEX method to transform the precipitation into flood discharges entering the river channel has the advantage of using the available data of precipitation to estimate the maximum flow. The method not only uses the available data but also has been developed based on objective hydrologic principles and can be applied consistently on a departmental or national scale. The approach presented here used two statistical models for computing extreme flows, to fit varying application needs and data availability scenarios. Geographic Information System and newly created digital database are used in the determination of channel geometric characteristics, required for hydraulic modeling. The validation of the model was successful.

The present study has shown that the hybrid methodology combining statistical analysis, hydraulic modeling and GIS has a sufficient range of functionality to be able to produce the flood extents and flood depth based on the available data. The purpose of the sensitivity analysis is to identify the response of the model to the variations in input parameter values and boundary conditions. This helped in identifying the input error that may contribute to most of the output uncertainty. The sensitivity analysis of the calibration shows a good agreement between the observed and simulated data. The use of high-resolution elevation data makes estimates of friction factor; Manning's *n*, relatively more important for correct results in inundation studies.

One key factor in developing this method was the search for the simplest solution that can work with available data.

The rapid growth of the population and expansion of the city on the left bank of the Atrato River requires planning based on realistic and dynamic evaluation of flood hazard. Some qualitative and quantitative analysis of the results clearly show that all the neighborhoods of the center of Quibdó in the right bank of Atrato river are vulnerable to the 50 years flood, while the left bank is completely covered by water during different flood events of return periods from 10 to 50 years. The difference resides not only in the area covered but also in the percentage of buildings submerged. The most vulnerable districts in the event of flood are: Kennedy, Yesca- Grande, Yesquita, Niño Jesus, Roma, and Esmeralda on right bank and Bahia Solano on left bank. The total number of buildings which could be impacted by the 50 years flood are 9,000, this account for 30% of buildings in Quibdó. The population which could be affected by the 50 years flood is approximately 37,000 inhabitants, equivalent to 45% of the population in the area.

These estimates could obviously be affected by a series of uncertainties, and by the possibility of errors of different kind, which may in some way influence the final result. These possible errors lie in: (i) the estimation of the extreme flow values; (ii) the representation of the river channel and floodplain (iii) the representativeness of the Manning's roughness coefficient and (4) the use of one dimensional model for flood estimation in urban areas.

We acknowledge the limitations of using ID model such as HEC-RAS for flood studies in an urban catchment, where flow is essentially two dimensional. Because of limited data requirements and computational efficiency ID models are still popular for flood studies for applications where details of the flow field are not of prime importance. In this work our focus was on reproducing the depth and extent of flooding, that model did reasonably well.

The results of this study lustrate the potential exposure of Quibdó, capital of the Department of Chocó, to flood hazard in the Atrato River. The research will benefit future flood management efforts by providing the first assessment of flooding risk in the study area. These flood inundation maps produced here can be used: (i) to identify minimum height of flood protection works such as dikes to protect city from flooding; (ii) to identify the regions that will be affected by the flood of a given magnitude or return period, (iii) to plan for emergency need e.g., shelter, medical supplies, food (iv) to assess flood damages; and (v) to determine if a potential site for proposed development is in a flood risk zone. While designed for Atrato River in Quibdó, this approach may be used as a prototype for flood hazard assessment in other areas of the department and country.

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