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Flood Modeling in a Coastal Town in Northern Colombia: Comparing MODCEL vs. IBER

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Abstract: In Riohacha the La Niña, phenomenon generates intense rains with consequent serious flooding. To address this reality, MODCEL, a conceptual cell-based model, had been applied and calibrated in a previous project. In this research, we compare MODCEL with IBER, a well-known, physically based 2D hydraulic model. The purpose is twofold: (i) to illustrate how system schematization can be carried out in the two modeling frameworks, which is not a trivial task and implies several choices and assumptions; (ii) to point out the strengths and weaknesses of these two models in a comparative fashion. Here, IBER has been calibrated and validated with the same data used for MODCEL. MODCEL performs slightly better, both in calibration and validation possibly because of the low resolution of the topographic information, an essential element for IBER. Furthermore, in IBER it is not possible to represent adequately all the different hydraulic works spread across the town. MODCEL, in turn, is not easy to apply because it requires a deep insight into the actual behavior of the physical system and time-consuming schematization attempts where a deep experience is needed; furthermore, it is by far less user-friendly than IBER. In any case, the two models capture sufficiently well the behavior of urban flooding and its changes according to hypothetical interventions.

Keywords: urban flooding; mathematical modeling; MODCEL; IBER; comparison

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1. Introduction

Floods are considered the most destructive natural disaster on earth. At the end of the 20th century (during the last decade) about 100,000 people lost their lives due to floods [1]. Between 1994 and 2013, 43% of global disasters were floods, affecting approximately 2.5 billion people [2]. Climate change, affecting all sectors of society [3], is generating an increment in the intensity and frequency of extreme weather events, including floods [4,5]. Floods have hence become an unprecedented social problem.

A number of software packages are presently available for dealing with floods and research is rapidly progressing in this area concerning particularly urban hydrology, hydrodynamic mechanisms, and their coupling [6]. Nevertheless, important challenges are still open as witnessed, for instance, by the IAHR workshop, "Weak points in the flood risk modelling chain" at the Special Session at 7th IAHR European Congress, Athens, September 2022 [7] and again by [6,8].

Models can be assigned to two classes:

(i) one (1D) or two dimensions (2D) "physically based" models based on a realistic representation of the terrain and of the processes of infiltration, storage, and runoff; their basic element is topography, i.e., a refined Digital Terrain Model (DTM).

(ii) "schematic-conceptual" models that are mainly based on a good representation of the underlying system of channels, tunnels, piping, manholes, tanks, jointly with the representation of water motion and storage processes, obtained by a number of related 1D and 0D (i.e., tanks) elements that, together, achieve a quasi 2D capability.

Mono dimensional (1D) models give good results for flows lying within the main channel of a river; less, when the event involves transients with overflows on the banks to (or from) the adjacent plains. Two-dimensional (2D) hydraulic models have made important advances in flood modeling and are considered a more complete and precise alternative to one-dimensional modeling (1D) [9]; 2D are indeed considered the state of the art for flood modeling [10,11]. However, a detailed topography must be available and the numerical integration of their equations may prove overwhelming in complex-large scale problems.

The physically based model class includes, among others: the very well known HEC-RAS 1D model, the IBER 2D hydraulic modelling tool, the SOBEK Overland Flow, the River2D, a 2D hydrodynamic model with finite elements, and the Hydrologic Engineering Center's HEC-RAS 2D. As a representative of the "schematic- conceptual" class, is MODCEL, Modelación en Celdas; and SWMM, Storm Water Management Model.

MODCEL, in particular, is a conceptual model that uses a quasi-2D approach to interpret physical reality [12,13]. That has been the main tool in the project named: "Green urban adaptation for facing floods relying on MODCEL mathematical modelling in Riohacha, La Guajira, Colombia", promoted and coordinated by Foundation CREACUA (Centro de Recuperación de Ecosistemas Acuáticos), financed by UNGRD, the Colombia's National Unit for Management of the Risks of Disasters, co-financed by Alcaldía Municipal of Riohacha, and developed through a strong cooperation with the Universidad Federal do Rio de Janeiro (UFRJ) and the Universidad de La Guajira (UNIGUAJIRA) [14]. The purpose of that project (referred to from here on as the "original MODCEL project") was to provide means for reducing flooding risk in the town of Riohacha with a system view, considering a large part of the town (an urban watershed), and finally delivering an integrated solution plan, agreed with the community and institutions [11], and based on the Sustainable Urban Drainage System (SUDS) and urban river restoration philosophy [11,15].

In order to obtain a usable modeling tool, supported by the MODCEL software, a notable effort was spent in an attempt to collect fresh field data on the events that occurred in previous years (particularly that of 2010 and 2011 on the occasion of a strong La Niña-ENSO phenomenon) and with them calibrate and verify the model. The MODCEL application obtained in that original project was considered reliable and suitable for the planning exercise addressed, although the uncertainties about the topography in particular could not be fully resolved. The effort to obtain it had been notable both in terms of schematizing the system (number of cells, spatial location, relevant connections with its physical characteristics), and calibrating it (basically modifying the runoff coefficient by type of land use).

The possibility of having a simulation model that makes it possible to predict the effects of hypothetical interventions against the problem of urban flooding is in any case an unquestionable advantage in hydraulic-territorial-urban planning. Of course, this is true only if the model is reliable and if it is possible to apply it in the situation under study with the information available or obtainable with reasonable effort, cost and time [16].

It is good practice to compare different models to point out advantages and limitations, even for more effective future applications [17–20]. It is known that IBER, a free software, has been used to model floods and has a user-friendly interface that allows visualizing the results in a practical and simple way [21–23]. We then decided to compare IBER performance to that of MODCEL, for the Riohacha case study, once calibration had been carried out with the same database and considering the same indicators of goodness of fit, in addition to versatility and ease of use. Some preliminary results of this study were published [24], but without details of the process carried out for the implementation of IBER. This process is not trivial because a series of choices have to be made in order to ensure the comparability of two modelling frameworks. This paper presents in detail the methodological steps describing how the application of the IBER model has been developed in the Riohacha case study (the analogous process for MODCEL is published in [11] and is not repeated here) offering hence an overview of the whole process of loading both software tools with an analogous description of the problem at hand. Although this process lies at a technical level, with no particular conceptual or methodological advances, it can be of great help to practitioners as it is not easy, as far as we know, to find this type of information in the literature.

To synthesize the contribution of this paper, we can state that: (i) it offers a useful comparison between two very interesting powerful modelling tools; (ii) it provides a complete overview of the process of loading the software with the information suited to describe a given case study (the same for both) without hiding the related difficulties and unavoidable assumptions; (iii) it contributes to illustrating the potentialities of MODCEL, which is not so well known, and deserves more attention. We hope to foster its adoption as it offers a number of significant advantages, including its high potential for educational purposes, while it is not sufficiently diffused in the sectoral literature.

2. Materials and Methods

2.1. Description of Modeling Tools

A review of models adopted in urban flood problems is presented by [25]. Our research is focused on just two models belonging to the two main classes identified above.

2.1.1. MODCEL (Modeling by Cells)

MODCEL is a conceptual, hydrodynamic model for simulating floods in rural or urban environments. It assumes that the considered territory is partitioned into cells, connected through a variety of options. Cells usually cooperate in forming complex structures, representing the topography of the natural ground or urban schemes defined by streets, squares, buildings, etc.

Cells in general are modeled as storage units governed, as such, by a zero-spatial dimension of flow, a one-dimensional storage equation (dynamic mass conservation), and storage-outflow relationships depending on the type of connection with nearby cells adopted to describe each specific cell (and that may depend as well on the state of nearby cells, e.g., when there is backwater effect over a certain threshold). In other words, these cells are considered not as conduits, not as surfaces with 2D motion, and not as 3D water bodies, but as small reservoirs that can store or release water volumes. However, MODCEL allows the inclusion of actual conduit type "cells" (e.g., reaches of canals, or pressure or free surface pipes) that are modelled as 1D flows with de Saint Venant's equations [11,12,26]. The model is therefore a composition of spatially zero-dimensional elements (*tank* type cells), mono-dimensional ones (e.g., the cells that compose a channel), and of equations that express the laws of water interchange (e.g., a weir, or the flow through an orifice); no shallow water equations are used. So a wide 2D region is not a cell; it has to be split into several smaller regions, i.e., cells -each one modeled as a 0D/1D element- that, all together, are assumed to be able to represent the overall physical behavior of the territory.

The full spatial representation of the physical system includes the interconnections amongst surface flow, channel flows, and surface or underground storm drains and sewage conduits, and also their pseudo-vertical connections [12,13,27].

Being a schematic-conceptual model, MODCEL's variables express the equivalent (or piezometric) elevation of the water level at a conceptual reference point of each cell. Anyway, in order to analyze the hazard and evaluate the risk, this information must be translated in terms of geographic-territorial reality (areas effectively flooded and assets affected within them), since only at that level one can evaluate indices such as type, number of houses, and other elements involved and the resulting damages [11]. This latter process has to be carried out outside of MODCEL, as a post-processing task through GIS software.

MODCEL offers an important advantage over "physically based" models since relatively rough topographic information is basically sufficient. In turn, the analyst is compelled to make up for the scarcely detailed topographic information by acquiring a deep understanding of how the system really operates, thus finally identifying the key elements to consider in its representation. Further topographic details may be required, but these concern only a few very specific situations that can be solved at little cost. On the other hand, even more, advanced technologies, such as LIDAR (Laser Imaging Detection and Ranging) surveys, while possibly useful, can probably never fill the vacuum of information in a real system, such as, in particular, the actual operativity of components such as manholes, often occluded by debris or garbage [28].

Another important advantage of MODCEL is its extremely short time of execution, as it does not imply the integration of partial differential equations, nor adopts a refined discretization of the area studied (no calculation mesh is required).

A weak point of MODCEL concerns the velocity variable: within MODCEL, this has a clear physical meaning only for conduit-like cells with 1D motion, while for overland flows, the velocity MODCEL deals with is rather an indicative magnitude suited just to provide the flows and exchange volume values. Owing, however, to the prevailing flatness of the area in our case study [29], the velocity was not considered necessary information as damages are in their great majority linked just to flooding depth.

2.1.2. IBER

IBER is a free, software implementing a family of bidimensional hydraulic mathematical models born for the simulation of free-surface flows in rivers and estuaries. It has been developed jointly by the Institute FLUMEN of Universitat Politécnica de Catalunya (UPC), the Grupo de Ingeniería di Agua y del Medio Ambiente (GEAMA) of the University of Coruña (UDC), and the Centro Internacional de Métodos Numéricos en ing Eniería (CIMNE). IBER now includes several different calculation modules, connected with one another, such as the hydrodynamic module, sediment transport module (as bottom load or suspended load), and water quality module, among others. The hydrodynamic module of IBER solves de Saint Venant's bidimensional shallow water equations, including the effects of turbulence and of surface friction by wind [30]. The equations are solved by the finite volume method on the grid nodes. The numerical schemes used in IBER are robust and stable in any situation, suitable for discontinuous flows, specifically for torrential channels and irregular regimes. The finite volume methodology is adopted to integrate the shallow water equations [30].

2.2. Study Area

The area considered for the MODCEL study (Figure 1) is split into two parts, an urban sub-watershed, with an area of 14.86 km^2 i.e., covering the urban section of the town of Riohacha (La Guajira, Colombia), and a rural sub- watershed (18.12 km^2) named El Patrón (cell 209), that may supply significant amounts of water during storms. This cell was initially considered in the original MODCEL project as it has the potential to become part of the solution. The urban sub-watershed was designed in order to agree with the topographic features of the study area, then parceled into cells through an expert-based, iterative process. Each cell is identified with a number and has specific features, such as area, hydraulic connections, etc.

In the MODCEL project [14], however, it was found that in the peak event simulation of MODCEL, water only flows from the El Patrón watershed to cell 208 that drains, through the box culvert, directly to the Riito (main branch) and not backward; moreover, none of the adjoining cells (108, 109, 207, and 208) drain toward El Patrón because of topography. Finally, the possible backwater effect that cell 208 may exert on upstream surrounding cells was neglected as its connection with Riito is quite effective and, during the considered events, Riito branch was not flooding and, as such, could not influence the urban system upstream (this may, however, happen during other events). For this reason, the sub-watershed El Patrón was not included when modeling with IBER, so simplifying the analysis.

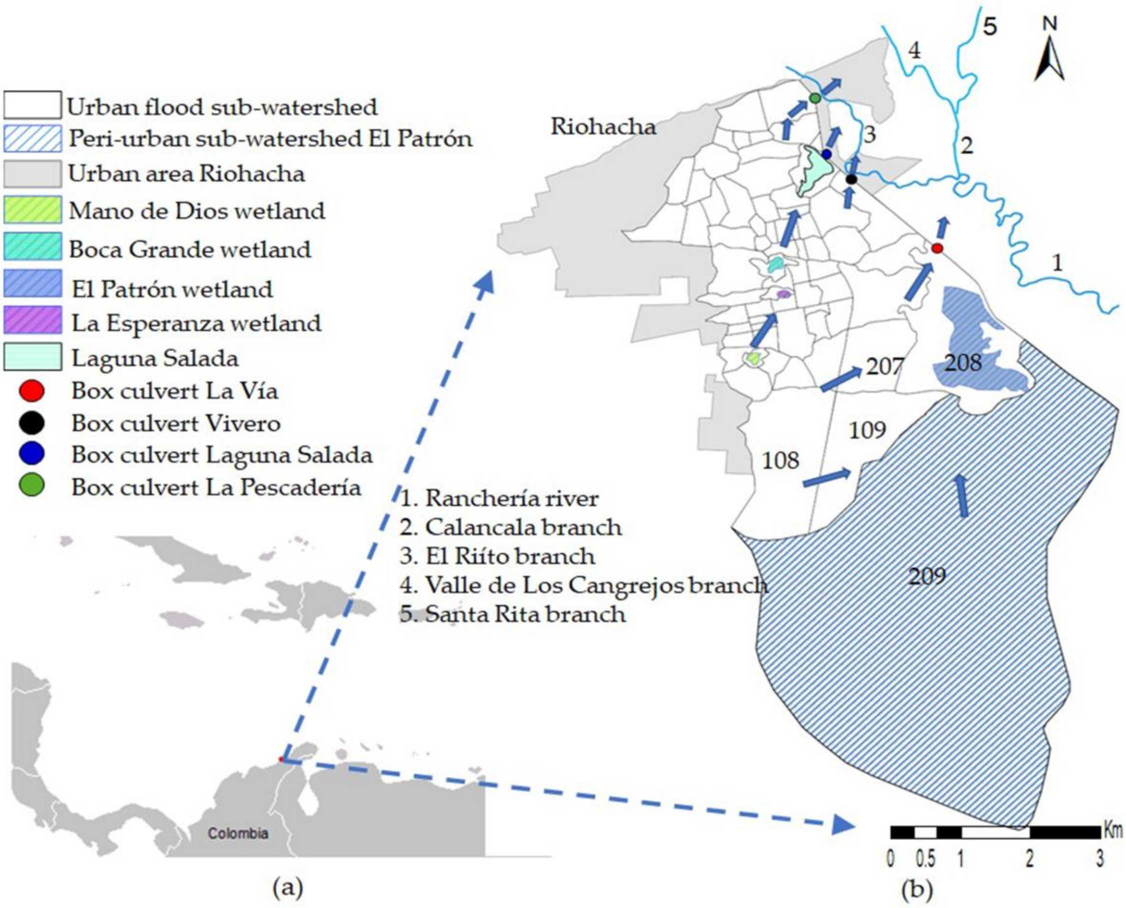

Figure 1. Location and details of the study area. (**a**) site of Colombia in South America; (**b**), delimitation and key details of the flood sub-watershed within the city of Riohacha, department of La Guajira (Colombia).

2.3. Steps in the Configuration of the IBER Application

As a first step, we resumed the information generated by the MODCEL project trying to adapt it to the needs of IBER in version 2.3.1. The information required refers to (i) defining the study area ("surfaces") and specifying: (ii) land use, (iii) initial conditions, (iv) internal, and (v) boundary conditions.

2.3.1. Mesh and Surface

The "surfaces" in IBER are assumed here to coincide with the same cells of MOCDEL, which were represented by drawing the contours of the 67 cells in which the study area is divided (geometry → create → NURBS surface → search). Another option is to directly import a shapefile (file → import → shapefile), but we preferred the first manual option because the latter sometimes generates incompatibilities. With the assigned surfaces, an unstructured calculation mesh was generated (Mesh → unstructured → assign sizes to surfaces) with element sizes of 4 m for the surfaces corresponding to the cells later considered in the assessment of calibration and validation performance; while an element size of 6 m was adopted for the remaining ones, resulting in 1,035,539 elements. Studies on the influence of mesh size in hydraulic modeling in flood plains with elements from 6 to 24 m have given satisfactory results in flood levels [31]. The mesh size used for IBER is smaller, therefore, it is considered adequate.

2.3.2. Land Use

Impermeable zones have adverse impacts on urban hydrologic regimes by reducing the infiltration into soils and increasing surface flows [32]. The accelerated urban growth builds over permeable surfaces and makes them highly impermeable.

It is worth noting that in MODCEL, the characteristics of the soil are completely described by a single parameter, the "runoff coefficient" (which incorporates the effect of infiltration and evaporation) [33]; in IBER, on the other hand, this description requires more parameters, precisely the roughness (Manning coefficient), and the parameters linked to the infiltration process [34].

IBER requires incorporating the roughness parameter through an ASCII-type file. We started therefore from the instrumental file created in the MODCEL project with extension .shp, where land use is classified as follows: (1) vegetation, (2) bare soil, (3) pavement, (4) buildings; and then we transformed such shapefile into a RASTER file (ArcToolboxes → Conversion Tools → To Raster → Polygon to Raster) and eventually that into an ASCII file (ArcToolboxes → Conversion Tools → From Raster → Raster to ASCII).

Finally, a roughness value was assigned to each land use class. The process started with the roughness values included by default in the software, but, as explained later in the calibration section, multiple simulations had to be carried out until the most appropriate coefficients were established. The initial (and optimized) Manning coefficient values for each land use were: vegetated 0.18 (0.30), bare 0.023 (0.25), asphalt 0.018 (0.38), and built-up 0.020 (0.46).

To incorporate the infiltration parameters, IBER offers several possibilities; the simplest (in the absence of specific information) is to adopt the Horton model, which has been widely used for runoff calculations in many urban watersheds [35,36]. It is an inverse exponential equation for infiltration capacity as rainfall continues; is described by equation 1 [37,38]:

$$f(t) = f_c + (f_o - f_c)e^{-kt} \tag{1}$$

where: f(t) (mm/h): infiltration capacity at time t, t (min): precipitation time, f_0 (mm/h): infiltration rate at the beginning of an event, f_c (mm/h): minimum infiltration capacity (base infiltration rate), k (min^{-1}): constant of temporal variation of the potential infiltration rate.

The three infiltration parameters were entered into the IBER interface by assigning a given value to all calculation mesh elements lying within each given surface corresponding to a cell of the MODCEL schematization [22]; the prevailing land use within the cell was considered representative. The infiltration rate (f_c) in IBER was then higher in areas where bare soil predominates. To reach the final values, several simulations had to be carried out until a satisfactory performance of the model was achieved. The infiltration parameters of the starting were 2.000, 0.200, and 2.000 for f_0, f_c y k respectively. The parameters calibrated for the Horton model can be seen in Table 1. These values are quite high; however, values over 15 mm/h for f_c have been found elsewhere, for instance in Córdoba, Argentina [37]; infiltration in Riohacha, given the semi-desertic, sandy soils, can reach quite high values.

Table 1. Horton model parameter values introduced to surfaces in IBER after calibration has been performed.

Cell	f_0 (mm/h)	f_c (mm/h)	K (min^{-1})
203	15.000	0.375	1.200
503	15.000	0.375	1.100
306, 310	0.500	0.375	3.000
205	0.375	0.200	3.200
201	0.375	0.100	3.300
All others	2.000	0.375	2.000

2.3.3. Initial Conditions, Internal and Boundary Conditions, Calculation Parameters

Initial conditions

The initial condition assumed was that of "dry cells", in the whole sub-watershed, i.e., a zero water depth, with the exception of wetlands, for which, as initial elevation, the natural minimum elevation of the aquifer was assumed (so that the effective depth for wetlands is the difference between the elevation attained and the initial elevation). The initial depth in the four wetlands present in the study area was then as follows: "Mano de Dios" 0.25 m; "Boca Grande" 0.50 m; "La Esperanza" 1.00 m and "Laguna Salada" 0.50 m.

Boundary conditions (flow inputs and outlets)

In IBER the boundary conditions (interaction between the limits of the study area and the surroundings) are named "conditions of flow entry and flow outlet" [39]. The only flow entry was in our case the rainfall for which we adopted, in calibration, the 18 September 2011 event, identified in the MODCEL project [14] as the most severe event of the "winter wave 2010–2011" by data measured at the Almirante Padilla pluviometer (Riohacha station [11]).

There are multiple flow outlets located along the road that virtually separates the delta from the urban area; these are constituted by: (i) a depressed zone connecting the modeled domain with the Riito (see arrow in front of laguna Salada, in Figure 1) and (ii) three main box culverts, namely: La Via, Vivero, Pescaderia, and Laguna Salada. The runoff of the urban sub-watershed normally drains toward the delta of the river Rancheria, specifically to the El Riito branch (the closest branch to town), although backward flows from the river itself into the town may sometimes occur under conditions of river flood and/or "mar de leva" (*surge*, a combination of astronomical and meteorological tide). As already said, in this application, according to the fieldwork and results obtained in MODCEL project [14], no water entry was considered between El Riito and the urban area.

The connection of the cell including the depressed zone, and outlet of Laguna Salada is represented in MODCEL as a supercritical or subcritical flow governed by the head conditions generated within the simulation domain during the simulation itself; i.e., MODCEL is able to adjust the relationship equations according to the conditions generated by the very simulation. In IBER, one has to choose the type of flow (supercritical in our case) and the length of the boundary segment involved has to be specified; in case of doubt, it is wise to test various hypotheses.

Box culverts can be represented within MODCEL directly as orifice-type structures; IBER considers box culverts as connection structures, but not as an outlet conditions. Accordingly, and assuming that water flows from the sub-watershed toward the river, we had to include in IBER these outlets as weirs (with a subcritical flowrate), which implies defining the discharge coefficient and the height of the weir. The latter can be expressed either as an elevation (absolute form) or as height over the bottom [34]. We adopted the former option and used the elevations of the highest points of the box culverts, already known from MODCEL project. The type of flow in these structures was defined as subcritical (see details in Table 2).

Table 2. Parameters defining the equivalent box culverts in IBER.

Box Culvert	Regime	Weir Parameter	Threshold Elevation (masl)
La vía	Subcritical	0.150001	3.28
Vivero	Subcritical	0.150001	2.13
Pescadería	Subcritical	0.150001	1.20

Internal conditions

In MODCEL, the flow between two cells is governed by the difference in water elevation (Figure 2a,b); this includes the rainfall-runoff process. IBER uses instead the topography defined by the DTM for "moving water from place to place", so it does not need a structure such as MODCEL cells; however, it is also possible to include a different type of hydraulic connection, named "internal condition" which refers to the form of water exchange from a given mesh element or "surface" (the equivalent in IBER of MODCEL cell) to other mesh elements or "surface" within the study area.

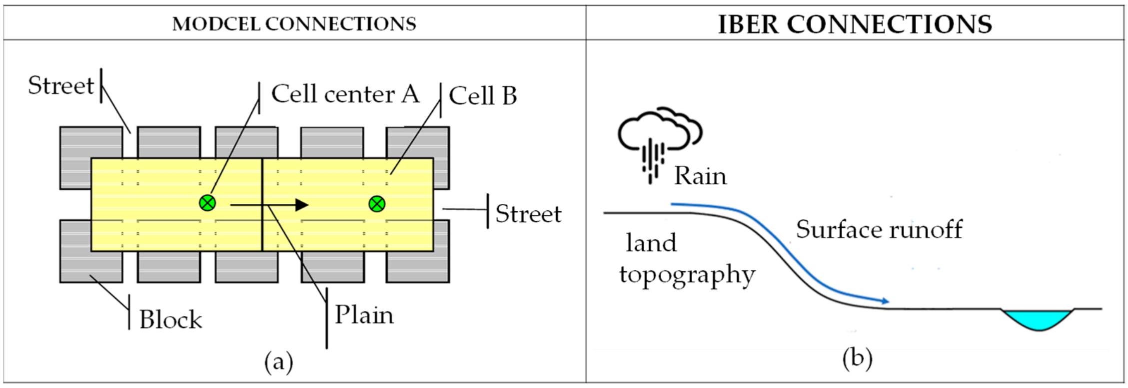

Figure 2. Adaptation of MODCEL connections to IBER options: (**a**) *plain* connection (the simplest), not required in IBER; (**b**) rainfall runoff and surface runoff processes in IBER. **Source:** own elaboration from [33,34].

The elevation associated with each mesh element in IBER is assigned with the same MODCEL MDT in the ASCII format from Arc/Info [32] (Ibe_tools → mesh → edit → set elevation from file). It should be noted that the DTM used in MODCEL was built with a 5 m spatial resolution and a normalized mean absolute deviation (NMAD) of 0.48 m as vertical precision. Therefore, although the spatial resolution is adequate, the vertical is not fully so; but it was what was available.

Figure 3 shows other types of internal connections and their correspondence in IBER. The *gate* and *orifice* types are schematized in Figure 3a,b; they are represented in IBER as *gate* types (Figure 3c). To describe them, IBER requires the following information: bottom elevation (Z_B), gate elevation (Z_D), percentage gate width (%), free outlet coefficient (C_d), and submerged outlet coefficient (C_{da}) [28]. For Z_B, we took the data from the original MODCEL project in each structure, while the percentage gate width, C_d, and C_{da} were assumed by default. Figure 3d presents the *weir-type* connection represented in IBER with an analogous structure, although it requires different parameters.

Figure 3e schematizes the connection with an underground canal or gallery (a free surface flow canal or a closed conduit with either a free surface flow or a full section pressure flow, depending on the specific time-varying conditions). The purpose of this structure (conceptually, a *sink*-type connection—Figure 3f—physically, a manhole) is to withdraw water from its location in order to lighten the surface runoff. For taking it into account within IBER, one has to specify the location of the sink (x, y, z) and a time series of the flowrates extracted because, in this version, IBER does not calculate them as it could be desirable [34]. Accordingly, to ensure a correct comparison between both models, we assumed for the sinks the same flow rate diagrams obtained by the simulation MODCEL referring to the model we were calibrating. This is certainly a significant weakness of IBER, while MODCEL internally computes it.

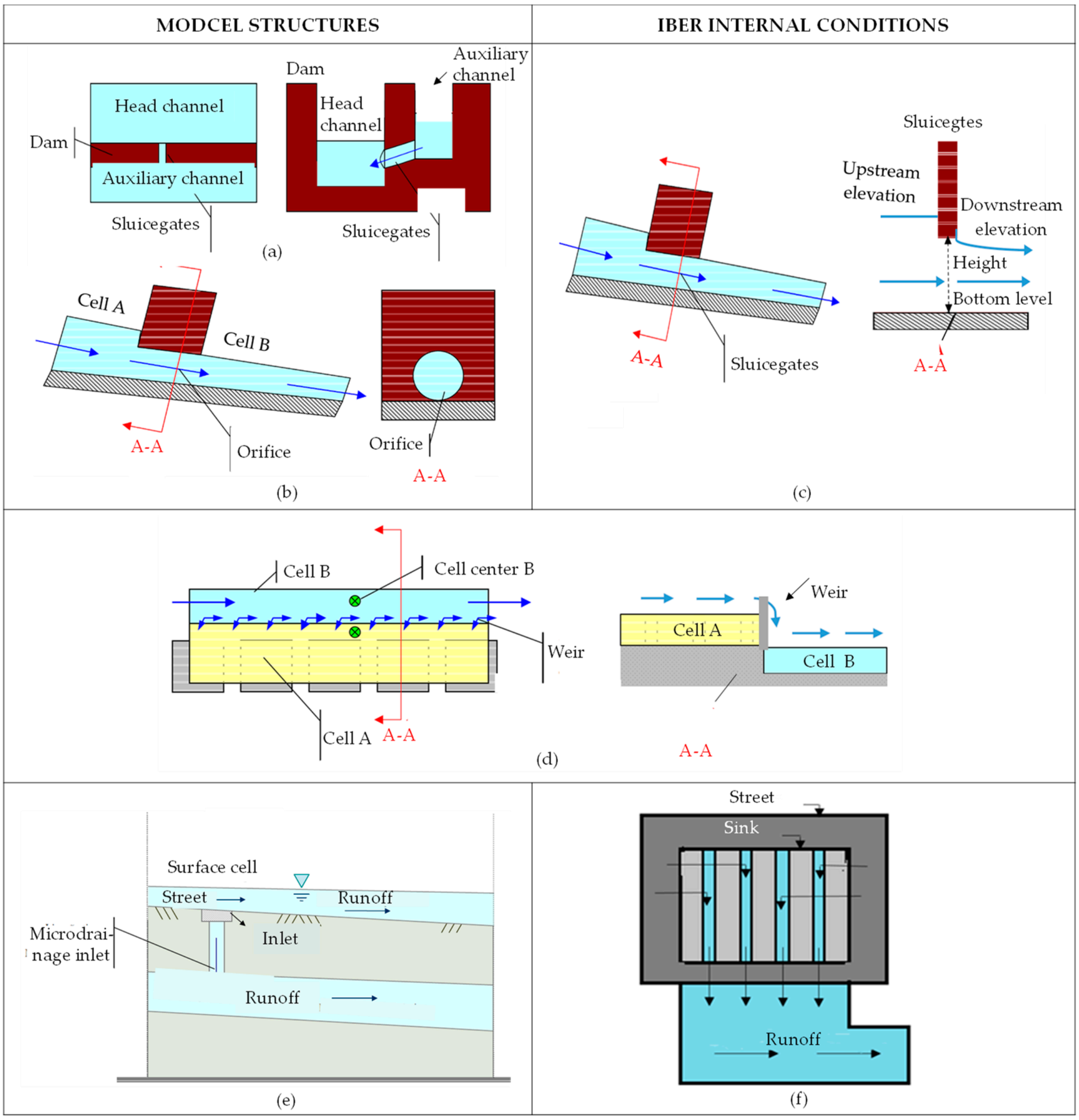

Figure 3. Correspondence of MODCEL connections to IBER types: (**a**) *gate* type and (**b**) *orifice* type; correspond in IBER to the *gate* type (**c**). The *weir* type (**d**) coincides in both models. The connection of a surface cell with an underground conduit € corresponds to a sink in IBER (**f**). **Source:** own elaboration from [33,34].

Data loading and calculation parameters

With the data menu → hydrodynamics menu, the initial conditions, boundary conditions (inlet and outlet), and internal conditions are assigned. Land uses in ASCII format were assigned to the surfaces (data → roughness → automatic assignation). The hyetogram corresponding to the event is loaded (data → hydrological processes → hyetograp assignation). Infiltration is uploaded in: data → hydrological processes → losses.

Finally, the values of the parameters governing the calculation of all the simulations carried out were assigned (data → problem data): maximum simulation time 45,000 s (12.5 h), exceeding the time of the hyetograms, with a result time interval of 900 s; the CFL stability condition defaulted to 0.45; the wet-dry limit (threshold that determines the limit depth from which an element is considered to be dry) was assumed to be 0.01 m, according to the recommendations of MODCEL designers (see [33]; indeed, pushing it down to almost zero values induces a risk of mass loss within the calculation domain [30]; max time increment (time step) 1 s; and for the numerical calculation scheme, the hydrological method was selected. This scheme is designed for hydrological calculations of rainfall-runoff transformation [34], and therefore it is useful to estimate the level of flooding in any area of interest [40].

2.4. Calibration and Validation

The precipitation data available are from the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), pluviometer of the Almirante Padilla de Riohacha station. The event considered for the calibration in the MODCEL project was that of 18 September 2011, the largest event recorded in the "2010–2011 winter wave" with about 231 mm/d and a core duration of about 3 hours. According to [41] and the elaborations carried out in the MODCEL project [14], this corresponds to a return period of 84 years. Assuming a trapezoidal shape, the corresponding hyetogram (mm/h) could hence be built. The same event was adopted for the calibration of IBER.

The validation of a model plays a very important role when checking its validity [16,26]. Therefore, as for the MODCEL project, after calibration, the validation of IBER was carried out with the event that occurred on 29 November 2011, which is the second strongest event of 2011 winter wave 2011 with a return period of 10 years, with about 150 mm/d, from which the 3 h hyetogram (mm/h) was obtained analogously to the previous case. This event was considered to produce considerable damages, for which there is documented information in the field. For MODCEL, the main parameter to be calibrated is the runoff coefficient associated with land use. In general, it depends on land use and slope; but in Riohacha, there are no significant slope differences, and gradients are better taken into account by the functional relationships representing the exchange amongst cells. Therefore, only land use was considered in the original project with 4 possible values corresponding to 4 different types of use, identified. (Such values in MODCEL are automatically increased by a constant factor for an event occurring soon after a previous one, so as to consider the partial filling of small terrain depressions and pools). On the other side, hydraulic coefficients representing the flow in channels (Manning) or over weirs or through orifices had been calibrated. Some physical features of the connections, such as the width of the channel that joins two cells, or the elevation of the threshold between them, had also been adjusted starting from the physical recognition on the field. All these adjustments are but steps in a preliminary procedure of physical interpretation, aiming at understanding how the watershed works and at refining its representation, before entering the actual process of calibration. All that concerns MODCEL calibration had been carried out in the previous MODCEL project and we did not touch it.

The dimension of the parameter space that was really explored in calibration was similar for both models, although the number of parameters available for calibration was indeed somewhat larger in IBER: three Horton parameters for each land use (or more precisely for all mesh elements falling in surfaces or MODCEL cells with the same land use type), one value of Manning parameter for each of the 4 types of land use, and the features of some hydraulic structures, such as the weirs, used to represent the connections between cells.

In order to appraise the goodness of fit, the MODCEL cells were classified into two types: *tank* type and *transport* type. The former type is characterized by a significant depth and behaves as an actual tank that stores (a lot of) water, such as is the case of wetlands; the *transport* type cells are characterized instead by a shallow depth while they transfer (large) volumes of water with a significant velocity, as streets do. Recalling what has been said in Section 2.1.1, it is worth clarifying that all of them belong to the non-conduit type cells governed by a zero-spatial dimension of flow, a one-dimensional storage equation (dynamic mass conservation), and a storage-outflow relationship. Accordingly, for *tank* type elements, the figure used to calculate the goodness of fit is the elevation of the water level (the same figure used in MODCEL) because, although measurements do not refer to the schematic center of the MODCEL cell, ideally they should coincide with the water surface elevation of their center (as the surface is supposed to be horizontal). For *transport*-

type cells, the water depth is considered instead, since it is the variable that determines the runoff (also because measurements of elevation taken at different points in the cell are not supposed to give the same value, owing to a significant slope of the flow, while depth would be constant).

In the MODCEL project, our field data were measured at the level of single houses, not at that of cells, where instead the information is provided by simulations. More precisely, the maximum height of the water reached in the houses during the event (calibration or validation) had been measured during a field survey and with this datum, the depth of the water in the adjacent open land was estimated [42], both for the case of *tank* type cells as for *transport* type cells. Therefore, there may be several data (houses) associated with each single MODCEL cell: for houses falling within the area of *tank* type cells, all elevation data should coincide with the simulation value; for *transport* cells, all data should give the same depth. In the case of IBER, given that the model yields a state value at each point of the mesh (finer than the size of a cell), the data obtained in the field survey is compared with the result of the IBER simulation in the same place.

For this reason, we adopted two different sets of goodness of fit indicators:

(i) a "cell center" group, where the measured datum of the house closest to the cell center is compared to the simulation output for that cell, corresponding to its center (the deepest point); this same information was adopted for both IBER and MODCEL; and

(ii) a "cell houses" group where for MODCEL, the cell center simulation output is compared with the datum in each one of the houses falling within the cell area (after a selection process based on independent criteria clearly established in the MODCEL project), while in IBER each house datum is compared with the closest local mesh datum from the simulation output.

Figure 4 shows the cells relevant to estimate the performance indicators and used to compare the models both in calibration and validation by the indicators presented in Table 3. The sub-watershed El Patron was not included when modeling with IBER for the reasons explained in Section 2.2.

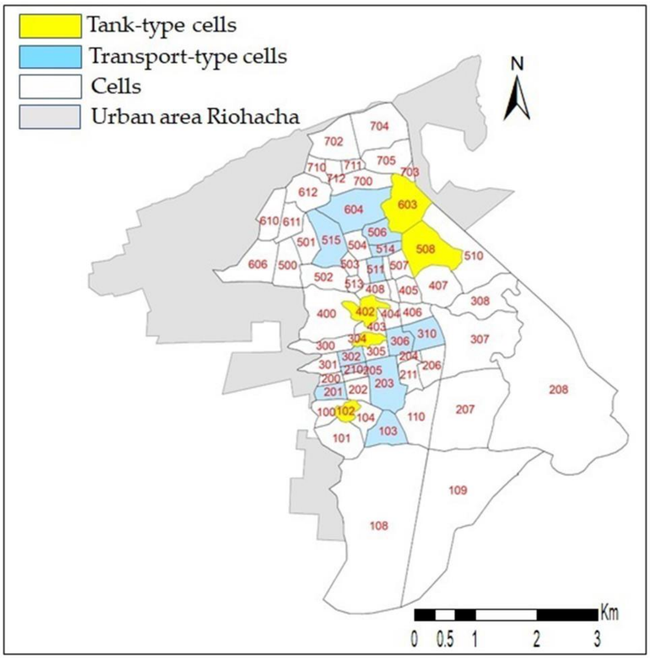

Figure 4. Cells considered for estimating the fitting quality of the models.

Table 3. Indicators of fitting goodness.

Name	Symbol	Description	Unit	Range	Sense	Source
Mean realtive error	e_{mean}	Arithmetic mean of the errors; provides a general idea.	%	$-\infty \div \infty$	The closer to zero the better	[43–45]
Maximum absolute error	$\vert e_M \vert$	Max absolute value of the errors, either by defect or excess.	m	$0 \div \infty$	The smaller the better	[46]
Root of the mean square error	RMSE	RMSE indicates the adherence of the model to data. It is sensitive to large errors, because of the squared operator.	m	$0 \div \infty$	Better the closer it approaches zero	[45,47–49]
Correlation coefficient	R	r says if model and data vary in the same sense.	ad	$-1 \div 1$	The closer to one the better	[47,50]
Standard deviation of error	σ_e	This measures the dispersion of errors.	ad	$0 \div \infty$	The smaller the better	
Variance explained	$\sigma^2{}_{exp}$	This expresses how much the model captures the variable pattern relative to its intrinsic variability.	ad	$0 \div 1$	Closer to 1 the better [1]	[42]
Mean relative bias	Bias	Bias points out whether there is a systematic difference.	%	$-\infty \div \infty$	The closer to zero the better [2]	[47]
Mean absolute error	MAE	MAE points out whether there is a significant average error either by excess or deficiency.	m	$0 \div \infty$	The smaller the better	[48]

[1] The model with $\sigma^2_{exp} < 0$ is worse than the average of the data; [2] under −20 underestimation; between −20 to 20 good; over 20 overestimation.

2.5. Modeling Scenarios

With the model calibrated as described, some scenarios were evaluated in order to observe the behavior of floods in the urban sub-basin in relation to two key scenario variables, as defined in the original MODCEL project. The first scenario (1) contemplates a meteorological event with a return period (Tr) of 100 years, similar to that of 18 September 2011 event, but with an arbitrary increase of 20% to represent climate change to represent the foreseen future [4,5], and considers the population at the date of this event; a second scenario (2), dually, contemplates the same hydrology adopted in the calibration (event with approx. Tr 80 years, without climate change), but an urban growth of 50% without respecting the Territorial Ordering Plan (POT) of the municipality of Riohacha [51], that is, adopting the assumption that people will tend to occupy the areas that are still free (what indeed occurred in reality).

3. Results

For calibration, 50 simulations were run, changing parameters by hand, in order to attain the "best" fitting. The manual approach was a forced choice in our case because any optimization algorithm [35] would have implied many more simulations and each simulation with IBER is very time-consuming on the laptop computer utilized: an Intel(R)

Core (TM) i7-4710HQ Processor @ 2.50 GHz 2.50 GHz, RAM: 6.0 GB, Integrated Card: Intel(R) HD 4600; while for MODCEL it was an Intel(R) Core (TM) i7-5500U Processor CPU @ 2.40 GHz 2.40 GHz, RAM: 16.0 GB. Execution times in MODCEL, with 3 s time step, was 2.5 min for each simulation, while for IBER the execution time in the simulation was about 24 h. We are fully aware that there is no guarantee to have reached a global optimum, but at least the process was driven by our understanding of the physical process and as such it gives us a certain confidence. In addition, validation is performed exactly to exclude overfitting.

3.1. Model Performance

Table 4 shows the goodness-of-fit indicators for the two models, for the *tank* and *transport* cells as explained above, both for calibration (18 September 2011) and validation (29 November 2011). The initial condition was a zero water depth everywhere, except for wetlands where the initial level of the water surface was specified based on physical knowledge of the area. In *tank*-type cells, the depth corresponds to the difference between the maximum elevation reached in the center of the cell during the event and the initial elevation of the water surface.

Table 4. Goodness-of-fit indicators of the MODCEL and IBER models in cells CENTERS and single HOUSES (compare lines with a given color between MODCEL and IBER).

Model	**CENTER/HOUSES**	**N**	**D_{mean} (m)**	**e_{mean} (%)**	**$\lvert e_M \rvert$ (m)**	**RMSE (m)**	**r**	**σ_e**	**$\sigma^2{}_{exp}$**	**Bias (%)**	**MAE (m)**
MODCEL	*Transport* cells CENTER	13	0.56	3.690	0.130	0.062	0.986	0.061	0.971	0.687	0.052
	Transport cells HOUSES	19		4.042	0.290	0.096	0.972	0.095	0.943	−1.775	0.071
	Tank cells CENTER	5	2.23	2.847	0.260	0.138	0.997	0.135	0.993	0.896	0.096
	Tank cells HOUSES	15		1.534	0.330	0.197	0.910	0.193	0.827	−3.996	0.174
IBER	*Transport* cells CENTER	13	0.56	−5.835	0.540	0.301	0.674	0.269	0.443	−24.100	0.258
	Transport cells HOUSES	19		−41.917	0.770	0.350	0.764	0.258	0.583	−40.03	0.282
	Tank cells CENTER	5	2.23	−5.035	0.536	0.306	0.984	0.295	0.968	−3.515	0.232
	Tank cells HOUSES	15		−3.560	0.717	0.361	0.674	0.350	0.433	−8.872	0.308

Table 4. *Cont.*

Model	CENTER/HOUSES	N	D_{mean} (m)	e_{mean} (%)	$\mid e_M \mid$ (m)	RMSE (m)	r	σ_e	σ^2_{exp}	Bias (%)	MAE (m)
MODCEL	*Transport* cells CENTER	22	0.40	−7.944	0.360	0.159	0.847	0.143	0.717	−16.760	0.120
	Transport cells HOUSES	22		−7.944	0.360	0.159	0.847	0.143	0.717	−16.760	0.120
	Tank cells CENTER	5	2.07	1.517	0.390	0.208	0.993	0.133	0.994	−0.676	0.150
	Tank cells HOUSES	12		−3.599	0.640	0.394	0.780	0.332	0.588	−28.950	0.347
IBER	*Transport* cells CENTER	22	0.40	−6.873	0.429	0.157	0.850	0.143	0.719	−16.162	0.116
	Transport cells HOUSES	22		−2.468	0.820	0.203	0.807	0.203	0.432	−1.755	0.109
	Tank cells CENTER	5	2.07	5.284	0.769	0.400	0.975	0.258	0.977	0.323	0.301
	Tank cells HOUSES	12		−18.064	0.579	0.310	0.817	0.305	0.653	−7.492	0.250

3.1.1. Calibration

1. ***Transport* type cells: CENTER**. MODCEL performed much better than IBER. However, the average relative error (e_{mean}) is low in both models; specifically, MODCEL overestimates the measured values and IBER underestimates them. The Bias indicator confirms the underestimation of IBER and an acceptable value for MODCEL, which could be due to the non-coincidence of the cell centers taken in MODCEL with the lowest points of the DTM: in IBER the runoff depends on the topography and in this case, no refined MDT was available.
2. ***Transport* type cells: HOUSES.** MODCEL keeps performing better than IBER, whose performance improves if compared to the results obtained in the cell centers. The e_{mean} and Bias confirm that IBER underestimates the data. It has to be reminded that, in addition to the poor topography, in IBER for each house, the local simulation output is considered, while in MODCEL, just the cell center datum is available.
3. ***Tank* type cells: CENTER.** These cells correspond to the four wetlands present in the urban sub-watershed and cell 508, which represents a low area of the city. In this case, the indicators are similar in the two models, and both fit the measurements quite well. The Bias is within the acceptability range ($-20 < \text{Bias} < 20$). The very high value of σ^2_{exp} may call for attention, but it is a consequence of the fact that the DTM in the wetland cells is not influential as what counts is the accumulated volume and the correspondence elevation volume. It is important to clarify that the elevations in these cells present a strong variation because of filling from the initial elevation (very low) to the maximum elevation (high values) in the flooding process.
4. ***Tank* type cells: HOUSES.** These results are very different from those of the cell center and show similarities to those obtained in the transport cells. The Bias, although lying

in the appropriate range, confirms, together with the e_{mean}, the underestimation of IBER with respect to the flood data collected in the survey.

In Figure 5, the comparison of the models for the *transport* and *tank* cells can be observed.

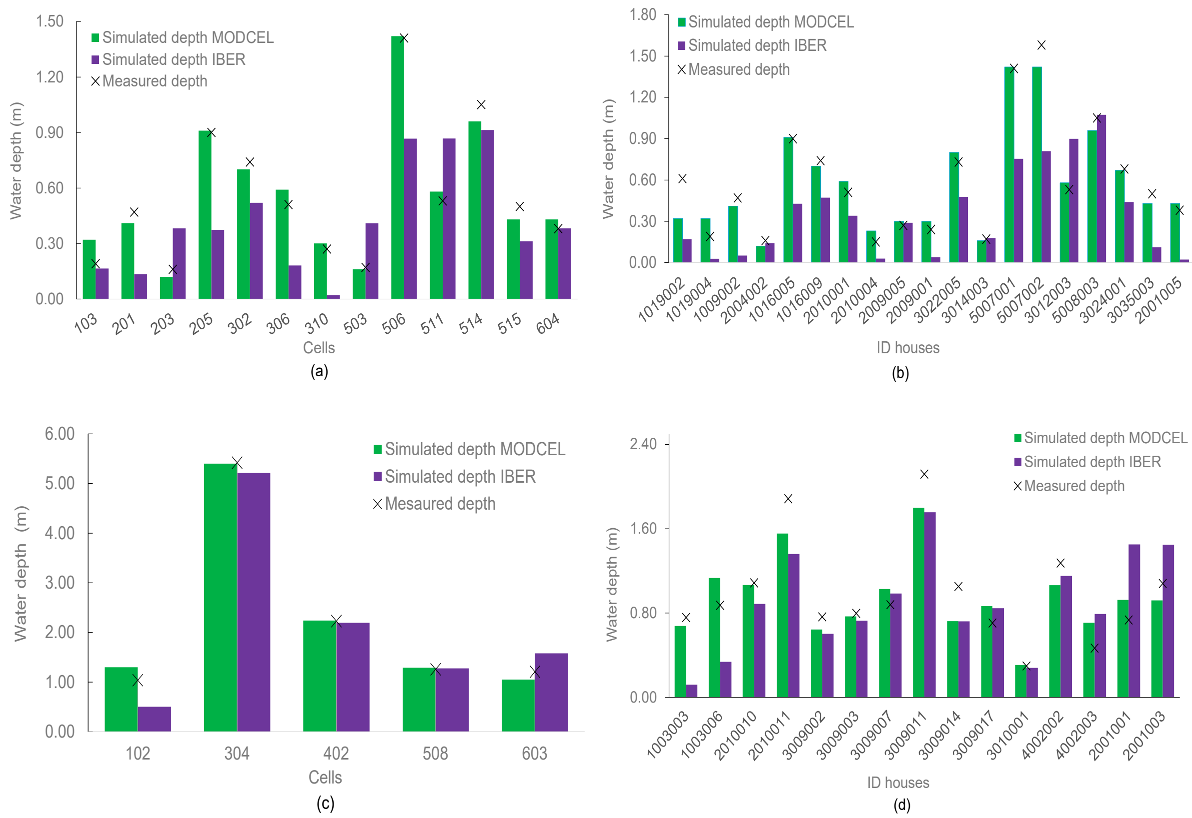

Figure 5. Comparison of water depth determined in the survey and simulated in calibration event: (**a**) transport type cell center; (**b**) in the houses located in the transport type cells; (**c**) *tank* type cells center; (**d**) houses located in the *tank* type cells. (Numbers in abscissa refer to cells codes).

3.1.2. Validation

The validation was carried out with the same criteria, and the same parameter values obtained in the calibration process were adopted for the calibration. Here below, the findings related to calibration are presented in a comparative fashion (Table 4).

- ***Transport* type cells: CENTER**: MODCEL worsens its performance across all the indicators, while IBER does the opposite, with exception made for e_{mean}; in addition, Bias, that in calibration indicated sub-estimation, (−24.10%) is now acceptable (−16.16%).
- ***Transport* type cells: HOUSES:** The result is similar to the previous case (CENTER), although now for IBER $|e_M|$ and σ^2_{exp} Worsen. Again Bias improved (from −40.03% to an acceptable −1.75%). Notice that for MODCEL the indicators coincide with the previous case (CENTER): this is because we just had one only house in both cases and the output only refers to the cell center.
- ***Tank* type cells: CENTER:** MODCEL slightly improves its performance for indicadors e_{mean}, σ_e, σ^2_{exp}, Bias (which switched from an acceptable negative value to an acceptable positive value). It worsens, however, a bit in terms of $|e_M|$, RMSE, and MAE. IBER in turn worsens in terms of e_{mean}, $|e_M|$, r, and MAE, while the remaining indicators improve. Analogously to calibration, both models show similar values of the indicators.

- ***Tank* type cells: HOUSES:** MODCEL worsens its performance in all the indicators and Bias passed from acceptable (−3.99%) to sub-estimation (−28.95%). IBER improves all indicators, with an exception made for e_{mean}.

In summary, in validation MODCEL worsens a bit its performance, while IBER improves it; but anyway in both models, the indicators assume similar values between calibration and validation, which proves their robustness. The fact that MODCEL worsens a bit more for Tank-type cells or HOUSES points out that in reality the surface of such cells is not really horizontal, but a more detailed subdivision in cells would be advisable. Figure 6 shows the behavior of measured and simulated depth for both models for the validation event.

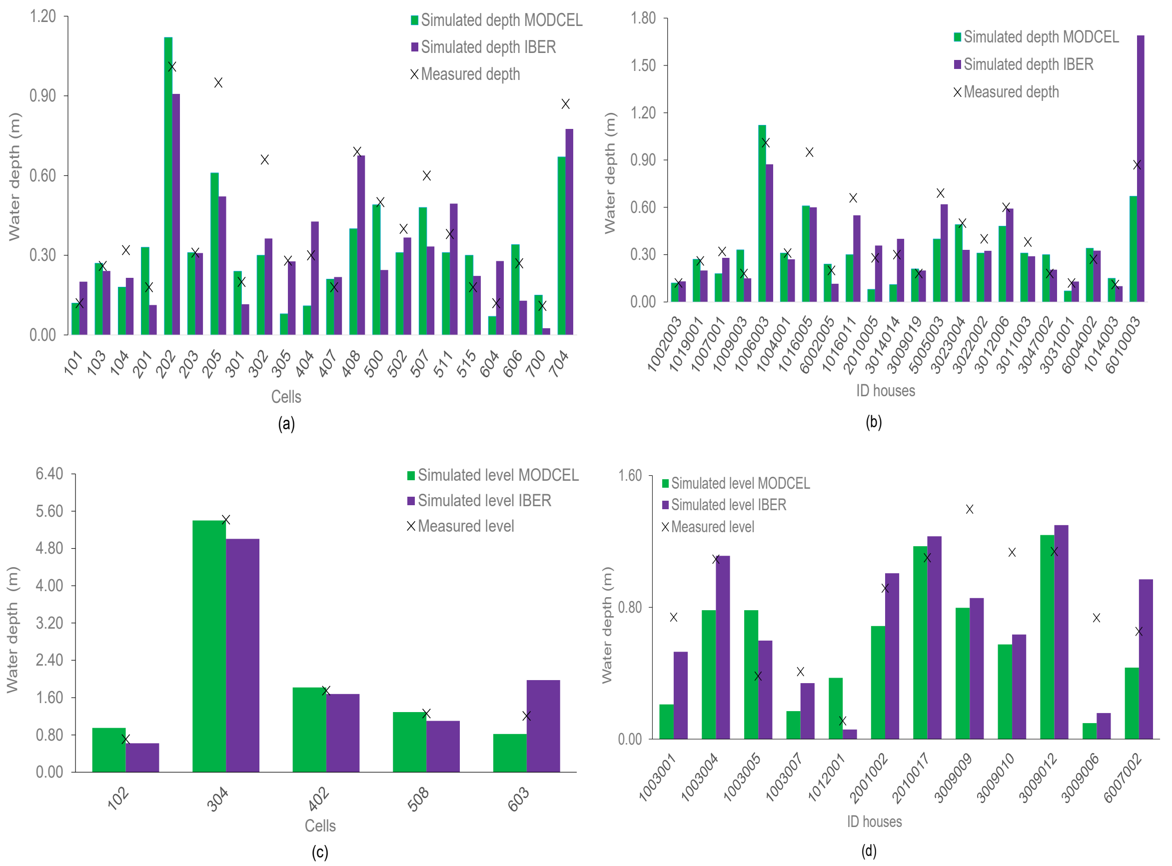

Figure 6. Comparison of water depth determined in the survey and simulated in validation event: (**a**) *transport* type cells center; (**b**) in the houses located in the *transport* type cells; (**c**) *tank* type cells center; (**d**) houses located in the *tank* type cells. (Numbers in abscissa refer to cells codes)**.**

3.2. Future Flood Scenarios

Two scenarios were simulated in IBER as described in Section 2.5 to explore the ability of IBER in pointing out peculiarities in the behavior of the system. Table 5 shows the max depth of the flood obtained with IBER in the two scenarios and in the calibration event (taken as a reference).

Table 5. Comparison of water elevations/depths obtained with IBER in both scenarios considered (and, for reference, in the event of September 2011 used for calibration).

Celda	Connected Cell	Event 18 September 2011 (m)	Scenario 1 (m)	Scenario 2 (m)
103	La mano de Dios	0.16	0.20	0.19
201	Mano de Dios	0.13	0.17	0.16
203	Taguaira	0.38	0.40	0.44
205	Mano de Dios	0.37	0.41	0.43
302	Comunitario	0.52	0.49	0.61
306	San Judas Tadeo	0.18	0.20	0.22
310	San Judas Tadeo	0.02	0.02	0.02
503	San Francisco	0.41	0.39	0.50
506	Calancala y Las Villas	0.87	0.89	1.02
511	Luis Eduardo Cuellar	0.87	0.93	1.03
514	Luis Eduardo Cuellar	0.91	0.95	1.16
515	San Francisco	0.31	0.32	0.37
604	Camilo Torres	0.38	0.44	0.45

Considering that any increase in the depth of the flood generates diverse consequences, it can be said that there are changes with respect to the event of September 18, 2011, except for cell 310. The most noticeable change occurs in cells 302, 503 506, 511, and 514. The above indicates that the houses located in these areas are the ones that have received and will receive the greatest damages due to flooding, following the rate of increase of the intensity of the rains.

A rather important aspect shown by IBER modeling, confirming one of the alternatives of the project MODCEL described in [11], is the existence of a connection between wetlands. IBER gives evidence that the runoff water flows through the lowest areas including the delta area known as El Riito and finally into the Caribbean Sea; as a result, it could be confirmed that wetlands are naturally connected with each other (Figure 7, calibration event). A similar result was obtained in the project MODCEL, by inspection of the topography itself (through an elaboration ArcGis) and by analyzing the flow directions revealed by people during the enquiry.

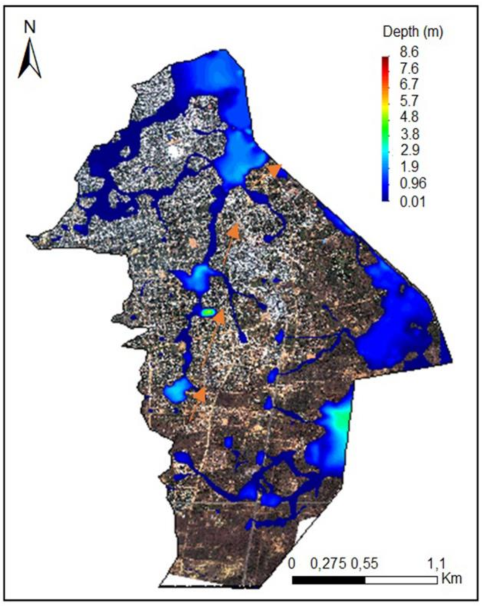

Figure 7. Flow path within the study area as obtained with IBER, calibration event.

4. Discussion

There is no effective flood model suited for all contexts. With this conviction in mind, this study aimed to compare MODCEL and IBER to obtain some indication about their strengths and limitations and to suggest guidelines for their application. Our discussion is based just on one case study, so its validity cannot be claimed to be general. In addition, the same case study could be schematized in a different way, leading perhaps to different conclusions. Yet the analysis undoubtedly sheds some light on the comparative behavior of two important, very different models and even modelling approaches.

The first point is the fact that the same physical reality is schematized in quite a different way in the two modelling frameworks and this requires specific choices from the analyst, which cannot necessarily be taken for granted. Related to this point is the availability of the required information. Physically-based models require detailed information that in developing or emerging countries, such as Colombia, is hardly available; or it can be available, but very soon it becomes obsolete because the pace of change of the territory overcomes any effort to build a fully detailed and reliable database. This very point raises an issue of uncertainty which is probably more important than that related to calibration itself. This issue is particularly relevant in urban environments with complex structures where streets, evolving hydraulic networks, and people's behavior (accumulation of detritus and garbage, unofficial modification of box culverts, or even the appearance of new houses, . . .) interact and contribute to destroying the hope to fully represent the "physical reality" [25]. This is the framework in which our exercise has to be looked at.

Both MODCEL [12,13,24,26,27] and IBER [9,22,23,40,52] have been widely used for flood studies, although MODCEL is probably less known in the sectoral literature. Comparative studies between inundation models of the same or different nature are not a novelty in the scientific literature, but a specific exercise involving these two models to identify their complementarity was lacking. According to Table 4, in the calibration event, the RMSE (m) for MODCEL ranged from 0.062 to 0.197 and for IBER from 0.301 to 0.361. For the validation event, the RMSE ranged from 0.159 to 0.394 and from 0.157 to 0.504 for MODCEL and IBER, respectively. These results are in agreement with Dazzi and Shustikova [19], who obtained RMSE values between 0.33–0.42 despite having a 1m resolution DTM. High-precision topographic data is essential to precisely define the extent and depth of the flood, allowing the development of detailed flood hazard maps [53]. The spatial resolution of a DTM decreases the RMSE from 0.56 to 0.13 when going from 10 to 5 m, and can reach 0.8 m when the resolution reaches 30 m [49]. Still, the resolution of globally available topographic data (Shuttle Radar Topographic Mission, or SRTM; Advanced Space-borne Thermal Emission and Reflection Radiometers Global Digital Elevation Models, or ASTERGDEM), is not sufficient particularly in urban and flat zones, while LiDAR DTM is not accessible for most zones in developing or emerging countries [25]. The height of the flood is even more sensitive to the vertical resolution, which has motivated the need to obtain more and more precise DTMs [54,55]. However, it is not always possible to have sufficient altimetric information reliably anchored to ground control points. Another limitation when using high-precision DTMs is the demanding computational time that increases with the area. Owing to the above, and given that IBER, such as all 2D models, depends on a detailed DTM, the values obtained for the goodness-of-fit can be considered acceptable for vertical resolution and the absence of terrain details such as sidewalks, curbs, small ditches in the DTM used.

According to such indicators (Table 4), MODCEL showed a very good performance: low errors, a bias lying within the interval considered good performance, low dispersion of the mean, high explained variance (σ^2_{exp} minimum of 0.827), and even a high correlation (r) between measurements and simulation outputs. Although IBER represents the flooding in the urban area of Riohacha sufficiently well, it shows a lower performance compared to MODCEL.

The best-fit indicators of IBER occurred in the *tank*-type cells, reaching values very similar to those obtained in MODCEL; that is, IBER behaved better in this type of cell than in the others. This observation confirms the concept that in 2D modeling, the accuracy of the DTM considerably affects the results because there are terrain features that must be identified clearly and in detail, such as buildings, curbs, sidewalks, streets, and houses, [56–59] while in wetlands, *tank* type cells, precision counts less since what counts is the (large) storage volume.

It is important to point out that our calibration process was conducted manually and, hence, certainly cannot claim to have found a global optimum. Given the very long calculation time implied by IBER simulations, with our computation resources, it would have been impossible to run an automatic algorithm that would have required a high number of trials, given the relatively large dimension of the search space.

Another important aspect of the modeling results is the calculation mesh: the size of its elements depends on the resolution of the DTM, and it should not be less than the DTM resolution. The type of mesh also influences the results and it is highly recommended to use unstructured meshes [20] since they adjust better to the irregularities of the terrain. In the urban simulations of Riohacha, the elements' size of 4 to 6 m is consistent with the study of [31]. However, the computation time significantly increases with the increase in the number of mesh elements and smaller step time, making simulation difficult and in some cases unfeasible for large areas, several elements, and small step times. To solve this difficulty, some models have implemented GPU (graphics processing unit) acceleration tools, such as PARFLOOD [19]. In the most recent versions, IBER has the IberPlus tool that makes the most of the graphics card, substantially reducing the calculation time depending on the capacity of this hardware. However, in version 2.3.1 used for the flood simulation in Riohacha, this option was not available, hence the high computation times required by IBER (24 h and 23 h for the calibration and validation event respectively) were extremely higher if compared to the 2.5 minutes of MOCDEL.

There is a variety of options in MODCEL to describe structures connecting cells, ensuring high modelling versatility [26,33]. On the contrary, a serious difficulty in IBER, also common in other 2D models, is encountered when special flow communication between different areas of the modelled domain has to be introduced, and in some cases, despite multiple efforts, one cannot reach satisfactory results [22]. For instance, it is hard to introduce a small-sized but important drainage network, unless a sufficiently detailed DTM is available (which was not the case). Even worse is the case of a manhole: as already noted, IBER (at least the version we adopted) requires an explicit hydrogram to be exogenously input and it makes it very unlikely to be able to represent the actual behavior of the physical system, particularly when the underground drainage capacity is overcome and an overflow occurs. Both effects can instead explicitly be modeled by MODCEL, provided that the underground network is included in the model schematization. Representing the physical urban reality is however always a challenge; one strength of MODCEL here is that it can take advantage of exogenous, qualitative information such as the direction of the flows map, obtained via interaction with local people: such a map proves key to defining cell interconnections. In the case of Riohacha this difficulty was overcome with a specific choice of the interconnection elements and by introducing as exogenous hydrograph of the manhole (sink type, case f in Figure 3) exactly that calculated by MODCEL for the same element.

We are aware that to many modelers, the idea to schematize the physical system as an ensemble of mostly 0D cells, with some 1D subsets, may seem somehow primitive. Additionally, undoubtedly there is a wide space of ambiguity where the analyst's art is called into play. E.g., a street can be considered a 0D (*transfer* type) cell; but it can also be considered a canal and as such be modelled as an ensemble of 1D elements (cells) governed by de Saint Venant's equations: it is a matter of detail, information availability, modelling effort, computational burden, and speed. Or, when the flow passes the sidewalk elevation, strictly speaking, it cannot be considered 1D any longer [6]. Yet similar issues, as discussed above, can be raised for physical-based models. This is indeed why the modelling exercise, in general, includes a validation step which, in our case study, was performed with the máximum honesty and detail feasible, according to the information available. The fact that a similar performance was found for the two models in both validation and calibration, gives confidence in the robustness of the modelling exercise, in agreement with Vozinaki et al. [53]. Undoubtedly, using only one event for calibration and one event for validation is a weakness of the process. Indeed, the variability of results can be high from one event to another. Hence, certainly, the whole process should be strengthened by including several events either for calibration or validation.

In general terms, MODCEL is more versatile when there is a lack of detailed topography (which is difficult to obtain in urban areas) and high complexity of the hydraulic infrastructures, an advantage that allows it to simulate articulated solution alternatives. It has to be reminded that it is also potentially capable of modeling the flow in the storm and sewage underground networks and their connections with surface runoff in both directions, although this capability has not been exploited in our exercise.

MODCEL is much faster and more stable (that is, it does not "crash") than IBER: in the process of preparing, executing, and obtaining results of a simulation, there were no crashes; on the contrary, in IBER there were blockages or failures. This may be related to the higher requirement of the computer equipment which increases significantly with the size of the area of interest, higher resolution of the DTM, and refinement of the mesh.

However, IBER Interface is by far more friendly and, in general, the model is relatively easy to use, allowing quick learning, although the need to train with tutorials and even by taking online courses and/or actual training remains. The MODCEL interface, at least in the configuration adopted in this exercise, requires more expertise to understand and use it. In addition, it is necessary to couple it with additional GIS software to represent the information spatially. Moreover, the application of MODCEL to a case study requires advanced knowledge of the model and a strong familiarity with the problem at hand, which limits its applicability to personnel extensively trained by the original MODCEL developers.

Another weakness is that, as already noted, the velocities determined in MODCEL cannot be considered reliable values when damages have to be computed (in the case of vulnerability significantly depending on velocity in addition to water depth).

Finally, while IBER is free software, using MODCEL requires one to establish a relationship with its creators (Universidad Federal do Rio de Janeiro) as the software is not directly available on the internet; however, this is perfectly feasible, and, although not an on-line free software, MODCEL is not a commercial product.

Last but not least, an important potentiality of the MODCEL tool lies in its high potential for educational purposes, as it obliges users to achieve a deep physical understanding of the hydraulic behavior of the system being modeled.

These characteristics are summarized in Table 6 for the ease of the reader.

Table 6. Advantages and limitations of the MODCEL and IBER models.

Model	Advantages	Weaknesses
MODCEL	- no commercial software, free for research purposes - can be used even when topographic information lacks detail - ability to represent surface and undergound drainage- sewarage systems (both free surface and pressure) and their interconnection with surface runoff - high calculation speed as it does not imply partial differential equations - requires a deep understanding of the physical system which helps selecting the appropriate representation of its components and avoids critical misunderstandings - good educational potential to drive students to master the ability to schematize reality	- the access, for the moment, requires contact with its creator - no user-friendly interface (although evolutions are likely) - outputs are numerical tables, so a GIS tool and post-processing are required to show results and to obtain data useful for risk calculations - velocities have a physical meaning only in 1D cells (conduits) - it is, in general, not easy to use without specific training or support by its developers, and few training or application documentation is available (and mainly in Portuguese only) - no open access code; however, its developers are open to improving it.
IBER	- free software, well-known world-wide - rich information available on its use and applications - nice interface (although its logic is far from being intuitive) - georeferenced, 2D spatial outputs useful for communication and risk calculations - velocities have a physical meaning - open access code	- it requires a detailed topographic information (DTM) - hard incorporation of a surface (open channel) drainage system - challenging representation of hydraulic structures (manholes, outlets) - impossibility to include the connection and interactive interaction with underground drainage-sewarage systems - very long calculation time

5. Conclusions

In spite of the data scarcity, it has been possible to gather all the data required to set up the simulation/validation simulations for both models.

According to the results, although aware of the reduced number of events adopted, it can be said that MODCEL and IBER adequately represented the flooding in the city of Riohacha, because the physical behavior of the system is well captured, errors are acceptable and validation does not show a worsening of the performance; they are also able to represent changes in relation to possible interventions. Therefore, both models are key planning tools for the problem at hand and we believe this holds for similar cases as well.

MODCEL slightly outperformed IBER in the Riohacha application here described. IBER's lower performance seems essentially due to the lack of a refined topography and the difficulty of adequately representing the hydraulic structures that connect or delimit the cells.

We believe that the exercise presented in this paper, even though not adding methodological or conceptual advances, can be of great help to practitioners, as it is not easy to find in the literature this type of comparison, and particularly a detailed description of the technical choices required to schematize the system at hand. This paper can help them to point out the critical issues concerning the schematization of a physical, urban system and it can foster the adoption and comparison of a different modelling framework.

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