12th International Conference on Hydroinformatics, HIC 2016

A GRASS GIS module for 2D superficial flow simulations

Laurent Guillaume Courty[a,b*], Adrián Pedrozo-Acuña[b]

[a] *Programa de Maestria y Doctorado en Ingenieria, Universidad Nacional Autonoma de México, DF 04510 México*
[b] *Universidad Nacional Autonoma de México, Instituto de Ingenieria , DF 04510 México*

Abstract

Urban flooding is a growing public concern in megacities such as Mexico City, due to the combined effect of an intense rising in both precipitation and levels of exposure. In this sense, the accurate assessment of urban flood impacts requires the development of fast modelling tools that increase our knowledge on the main processes governing the generation and propagation of floods. This paper presents a new hydrodynamic model named Itzï, designed to simulate superficial flows in two dimensions, by means of a pseudo-2D and partial acceleration numerical scheme on a raster grid. The model has been implemented within a GRASS GIS environment, through a module written in *Python* that manages inputs (e.g. rainfall) in a raster format with dynamic variables in time and space. The model is validated using two different analytical test cases for the full shallow water equations, for which results from the numerical tool compare very well, with RMSE of 0.03 and 0.003 meters, respectively. Secondly, a test related to an urban setting is also employed for its verification; in this case, we employ a hypothetic flood event in the region of Greenfield, in the city of Glasgow in the UK; for which hydraulic data is available, along with a high resolution Digital Elevation Model (2m). Moreover, in order to compare the performance of our model against other well-established models, we also implement the "acceleration" model of LISFLOOD-FP. Encouraging results are found in this comparison, as nearly identical results with both models are produced. Therefore, the numerical tool here presented represents a solid step forward, towards the development of smart urban flood management strategies, which rely in open-source modern technologies enabling better decision-making within the context of climate change and urbanization.

Keywords: GIS;Python;superficial flow;modelling;urban flooding

1. Introduction

Around the globe, meteorological events continue to result in disasters in many locations. Despite their predictability, those who will be most affected often do not receive warnings when hazardous events are likely to happen. At least in part, this failure of communication is a result of many government agencies and aid organizations still being insufficiently connected to the hydrological sciences[1]. Hydro-meteorological hazards can have cascading effects and far-reaching implications on water security, with political, social, economic and environmental consequences. These events observed in developed and developing nations alike, highlight the necessity to generate a better understanding on what causes them and how we can better manage and reduce the risk.

On the other hand, the world is becoming increasingly urbanised, with more than 50% of the global population living in urban areas[2]. Towns, cities and megalopolis create employment and business opportunities, yet the very aggregation of people and assets create its own vulnerabilities, moreover projected climate-induced changes will only aggravate the impact of already existing stresses. Despite the effects of changes in the society and the environment, cities in the world are not functioning well; this may be ascribed to the lack of adaptation of urban infrastructure to these changes. This situation endangers the future sustainability or urban systems, especially in regions of the world such as Latin-America, where 77 percent of the population is located in large cities.

Perhaps, one of the clearest examples where these complexities arise is in the characterization of urban flood hazard, which requires the adaptation of drainage infrastructure to a standard that may be greater than the design level used in the construction of this infrastructure. Therefore is no surprise that urban flood modelling has recently received increased attention (e.g., [3–7]).

The prevailing approaches to tackle this problem, are based on a concept called "dual drainage", where urban stormwater drainage systems comprise two parts: First, a surface system (e.g., streets, ditches, inlets), and second, a subsurface storm sewer network [8]. However, there are known difficulties in modelling both systems in a coupled manner. Hence, these two components of the problem are usually modelled independently. Under

* Corresponding author. Tel.: +0-000-000-0000 .
E-mail address: lcourty@iingen.unam.mx

this perspective, the purpose of this study is to present a first step in the integration of an urban flood hazard model that solves both systems in an integrated manner. However, results in this paper introduce only the hydrodynamic part associated to the surface system. For which a new modelling tool is presented, and was developed within an open source GIS platform, known as Geographic Resources Analysis Support System (GRASS) [9]. This development presents an open-source alternative approach with low requirements for computation and hydrological observations that can be applied to identify flood risk in urban environments.

In order to revise the performance of the numerical tool, we implement two different test cases one comprised by two analytical solutions of the shallow water equations, and another related to a hypothetic flood event in the urban area of the city of Glasgow, United Kingdom. In this case, hydraulic data and a high-resolution Digital Elevation Model (DEM) are available. Moreover, results from our model are also compared with results from a well-established model (LISFLOOD-FP).

This paper is organised as follows, the Model presentation section provides a description of the numerical approach with information of the numerical scheme and implementation in a GIS environment; Model testing and results presents the validation results for both the analytical and urban cases. Finally, discussion and conclusions are summarised in the last section.

2. Model presentation

2.1. Numerical scheme

The developed model uses a finite differences scheme based on a staggered grid (cf. Fig. 1). The numerical scheme is based on the work from Almeida et al., [10,11]. It is a pseudo-2D scheme, as it consists of a partial inertia Saint-Venant equation, applied in both dimensions successively during the same time-step. For simplicity, only the *x* dimension is described here. The same principle applies for the *y* dimension.

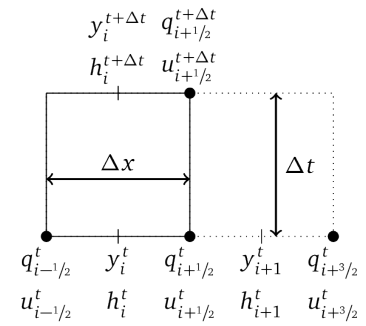

Fig. 1: variables used for the numerical solution

The time-step duration Δt is calculated using equation (1) at the beginning of every time-step in order to comply with the Courant-Friedrichs-Lewy (CFL) condition.

$$\Delta t = \alpha \frac{\min(\Delta x, \Delta y)}{\sqrt{g \times h_{\max}}} \qquad (0)$$

Where Δx and Δy are the cell dimensions, *g* the acceleration due to gravity, h_{max} the maximum water depth throughout the domain and α a coefficient to ensure the compliance with the CFL condition. The latter is set by default to 0.7[11].

The flow at cells interfaces is calculated using the equation (2), in which *q* is the flow in $L^2.T^{-1}$, *n* the Manning's friction, *S* the hydraulic slope, θ a weighting coefficient and h_f the flow depth. The latter is acting as an approximation of the hydraulic radius and is the difference between the highest water elevation and the highest surface elevation of neighbouring cells.

$$q_{i+1/2}^{t+\Delta t}=\frac{\left(\theta\cdot q_{i+1/2}^{t}+(1-\theta)\frac{q_{i-1/2}^{t}+q_{i+3/2}^{t}}{2}\right)+gh_f\Delta tS}{1+g\Delta tn^2\|q_{i+1/2}^{t}\|/h_f^{7/3}} \qquad (0)$$

The new water depth is calculated by doing the sum of the current depth h_t, the external factors (rainfall, infiltration, user-defined flows etc.) h_{ext} and the flows passing through the four faces of the cell, as shown in (3).

$$h^{t+\Delta t}=h^{t}+h_{ext}^{t}+\frac{\sum Q_{i,j}^{t}}{\Delta x\Delta y}\times\Delta t \qquad (0)$$

When water level in the cell is lower than a user-specified threshold, the general equation described in (2) is replaced by a simplified rain-routing scheme [12] described as follow. At the very beginning of the simulation, the elevation map is analysed and a flow direction is affected to each raster cell, allowing the water content of the cell to drain in a single direction. Then, at each time-step the flow is calculated using a user-defined velocity, set by default to $0.1 m.s^{-1}$ [12].

2.2. Implementation

The model is implemented as a Python module[13] for GRASS. The computational intensive parts of the numerical resolution have been parallelized using Cython[14] and therefore take advantage of the multithreading capacities of modern CPU. The developed tool is distributed under the GPL license, allowing fellow scientists and general public to use and modify the software.

Itzï leverages on the GRASS temporal framework[15] by using space-time raster datasets (STRDS) as inputs and outputs. This means that any input could vary in time and space, in the form of a raster map time-series. The latter applies to each model forcing, which could include rainfall, infiltration parameters, friction value, boundary conditions etc. The module can output STRDS of water depth, water elevation, velocity and flow. Velocity and flow outputs are each being maps representing the value of the variable in both *x* and *y* directions. From these components, a post-processing module generates raster maps of the resultant vector magnitude and direction, which in turn allows GRASS to display flow arrows. Further post-processing could be done by making use of the vast collection of tools offered by GRASS.

3. Model testing and results

3.1. Analytical test cases

The analytical test cases for subcritical flows used here are taken from the SWASHES compilation[16]. Both cases described here are of MacDonald’s type [17] and is constituted by a 1km long channel, discretized at 5m resolution. The first one considers a constant upstream flow of $2 m^2/s$, while the second one combines an upstream flow of $1 m^2/s$ and an uniform rainfall with an intensity of 0.001m/s.

In the developed model, the input flow is given as a mass addition. This creates an artificially high water level at the most upstream cell, where the input flow is added. Given that the goal of the analytical tests is to verify the validity of the numerical scheme, the Root Mean Squared Error (RMSE) is here calculated by omitting the very first cell of the domain.

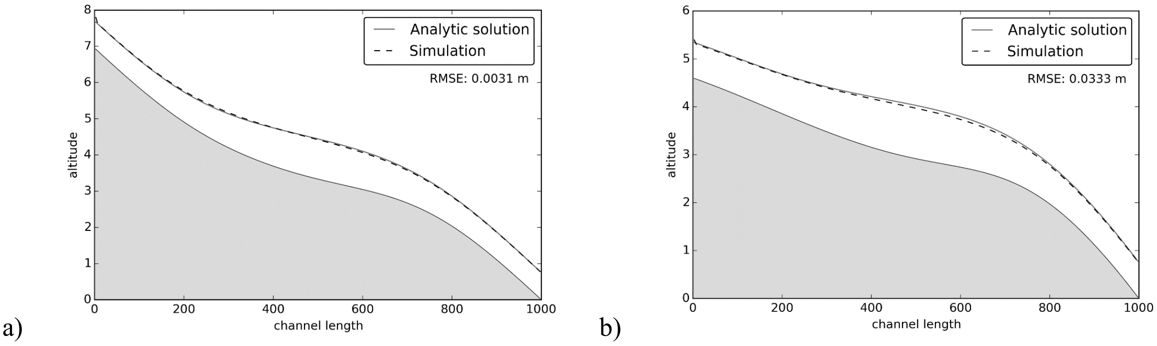

Fig. 2. a) One-dimensional McDonald long channel. b) With rain

3.2. High-resolution inundation in an urban setting

In this section the model is tested with a hypothetic event happening in the region of Greenfield, Glasgow (UK). It correspond to the test case number 8a from the UK Environmental agency [18]. The results of the new model are then compared with the “acceleration” model of LISFLOOD-FP[11], which is considered as the reference implementation of the numerical scheme.

The input data consist of a DEM at 2m resolution a friction map, a synthetic uniform rainfall and a point inflow. The hyetograph and hydrograph are represented in Fig. 3, respectively. Here, this 83 minutes event on this domain of 38.56ha and 96,400 raster cells has been computed in 36 seconds. For the comparison of the two numerical models, Itzï and LISFLOOD-FP, nine different locations are selected (see Figure Fig. 4), for which numerical results from both models with regards to water level are also illustrated in Figure 6. In the panels of this figure, the blue solid line represents the results from the LISFLOOD-FP model while the red solid line illustrates the results from the presented model. It is shown that both models behave in a very similar manner, which provides confidence in the results obtained by our numerical tool.

On the other hand, to observe the development of this event in time and space, Figure Fig. 5 presents the snapshots of the numerical domain at three different times identified in the panel a)t=10min , b)t=45min and c)t=82min, as well as the maximum estimated water depth within the domain (panel d).

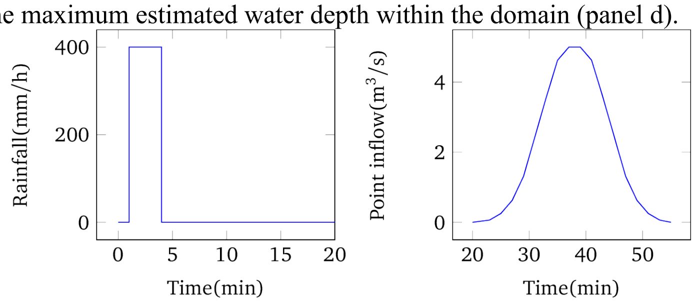

Fig. 3: Input data

Fig. 4: Study zone with control and inflow points
(Imagery: DigitalGlobe, Getmapping plc, Infoterra Ltd & Bluesky, The GeoInformation Group, Google)

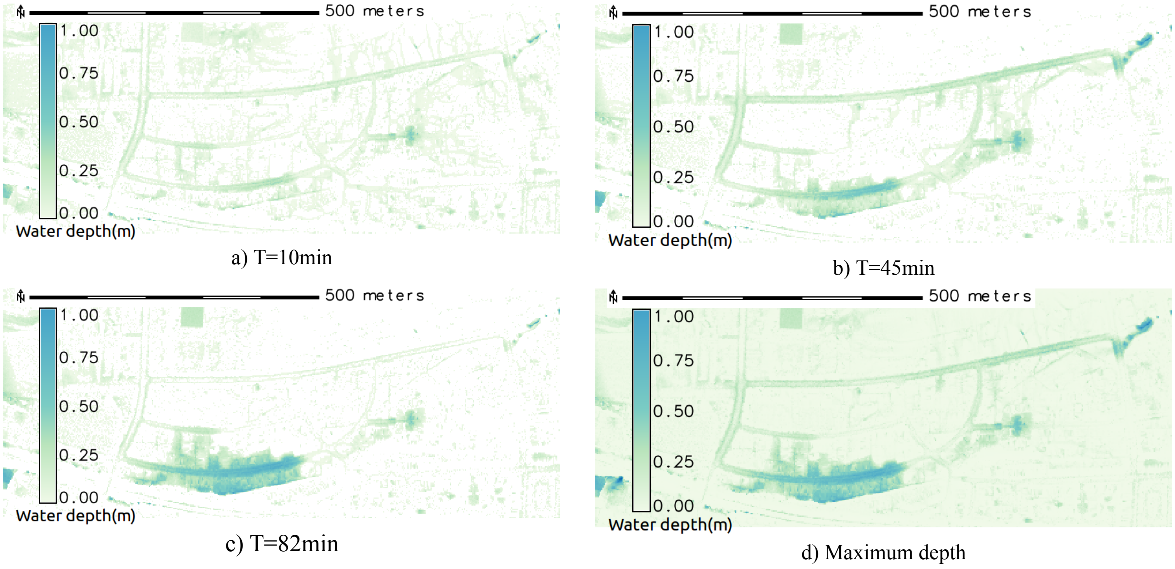

Fig. 5: Snapshots of numerical results for estimated water depth at different times (panel a – t=10min, panel b – t=45min, panel c- t=82min) and maximum water depth (panel d).

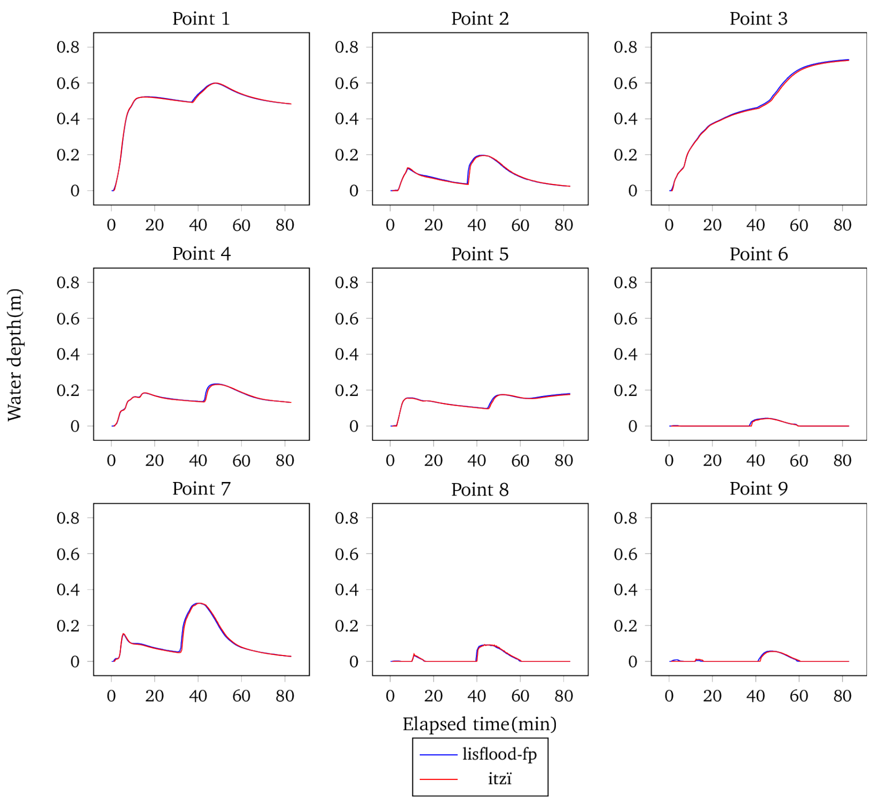

Fig. 6: Comparison of water depth at control points

4. Discussion and conclusion

This paper presented a new hydrodynamic model named Itzï, designed to simulate superficial flows in two dimensions, by means of a pseudo-2D and partial acceleration numerical scheme on a raster grid. The numerical tool has been implemented within a GRASS GIS environment, through a module written in *Python* that manages input/output variables (e.g. rainfall) in a dynamic raster format in time and space. The model has been validated using two different analytical test cases for the shallow water equations, for which results from the

numerical tool compared very well. Additionally, a hypothetic test case in an urban setting was also employed, this corresponded to the test case produced by the Environment Agency in the United Kingdom. In this case the model performance was also evaluated against results from a well-established model, finding encouraging outcomes as nearly identical outputs are produced with both models.
Therefore, the numerical tool represents a solid step forward, towards the development of smart urban flood management strategies, which rely in open-source modern technologies enabling better decision-making within the context of climate change and urbanization. Notably, the open source characteristic of the model will enable its free distribution as it is further developed (see http://www.itzi.org). Lastly, further evaluation on other catchments and real cases is anticipated to better understand under which conditions this type of model is applicable. Future work should also include sensitivity to catchment discretisation and rainfall resolution, as well as the development of a two-way coupling with the SWMM drainage model and a GPGPU version of the model.

Acknowledgements
Laurent Courty has been funded by a PhD scholarship from the Universidad Nacional Autónoma de México.

References

[1] H. McMillan, A. Montanari, C. Cudennec, H. Savenjie, H. Kreibich, T. Krüger, et al., Panta Rhei 2013-2015: Global perspectives on hydrology, society and change, Hydrol. Sci. J. 6667 (2016) 02626667.2016.1159308. doi:10.1080/02626667.2016.1159308.

[2] C. Zevenbergen, A.C. Cashman, N. Evelpidou, E. Pasche, S. Garvin, R. Ashley, Urban Flood Management, 2010. doi:10.1002/ana.22591.

[3] M.-H. Hsu, S.-H. Chen, T.-J. Chang, Inundation simulation for urban drainage basin with storm sewer system, J. Hydrol. 234 (2000) 21–37.

[4] O. Mark, S. Weesakul, C. Apirumanekul, S.B. Aroonnet, S. Djordjevic, Potential and limitations of 1D modelling of urban flooding, J. Hydrol. 299 (2004) 284–299. doi:10.1016/j.jhydrol.2004.08.014.

[5] T.G. Schmitt, M. Thomas, N. Ettrich, Analysis and modeling of flooding in urban drainage systems, J. Hydrol. 299 (2004) 300–311. doi:10.1016/j.jhydrol.2004.08.012.

[6] C.C. Sampson, T.J. Fewtrell, A. Duncan, K. Shaad, M.S. Horritt, P.D. Bates, Use of terrestrial laser scanning data to drive decimetric resolution urban inundation models, Adv. Water Resour. 41 (2012) 1–17.

[7] D. Yu, T.J. Coulthard, Evaluating the importance of catchment hydrological parameters for urban surface water flood modelling using a simple hydro-inundation model, J. Hydrol. 524 (2015) 385–400. doi:10.1016/j.jhydrol.2015.02.040.

[8] M.B. Smith, Comment on “Analysis and modeling of flooding in urban drainage systems,” J. Hydrol. 317 (2006) 355–363. doi:10.1016/j.jhydrol.2005.05.027.

[9] M. Neteler, M.H. Bowman, M. Landa, M. Metz, GRASS GIS: A multi-purpose open source GIS, Environ. Model. Softw. 31 (2012) 124–130.

[10] G. a M. De Almeida, P. Bates, J.E. Freer, M. Souvignet, Improving the stability of a simple formulation of the shallow water equations for 2-D flood modeling, Water Resour. Res. 48 (2012) 1–14. doi:10.1029/2011WR011570.

[11] G. a M. De Almeida, P. Bates, Applicability of the local inertial approximation of the shallow water equations to flood modeling, Water Resour. Res. 49 (2013) 4833–4844. doi:10.1002/wrcr.20366.

[12] C.C. Sampson, P.D. Bates, J.C. Neal, M.S. Horritt, An automated routing methodology to enable direct rainfall in high resolution shallow water models, Hydrol. Process. 27 (2013) 467–476. doi:10.1002/hyp.9515.

[13] P. Zambelli, S. Gebbert, M. Ciolli, Pygrass: An object oriented python application programming interface (API) for geographic resources analysis support system (GRASS) geographic information system (GIS), ISPRS Int. J. Geo-Information. 2 (2013) 201–219.

[14] S. Behnel, R. Bradshaw, C. Citro, L. Dalcin, D.S. Seljebotn, K. Smith, Cython: The Best of Both Worlds, Comput. Sci. Eng. 13 (2011) 31–39. doi:10.1109/MCSE.2010.118.

[15] S. Gebbert, E. Pebesma, TGRASS: A temporal GIS for field based environmental modeling, Environ. Model. Softw. 53 (2014) 1–12.

[16] O. Delestre, C. Lucas, P.-A. Ksinant, F. Darboux, C. Laguerre, T.-N.-T. Vo, et al., SWASHES: a compilation of shallow water analytic solutions for hydraulic and environmental studies, Int. J. Numer. Methods Fluids. 72 (2013) 269–300. doi:10.1002/fld.3741.

[17] I. MacDonald, M.J. Baines, N.K. Nichols, P.G. Samuels, Analytic Benchmark Solutions for Open-Channel Flows, J. Hydraul. Eng. 123 (1997) 1041–1045. doi:10.1061/(ASCE)0733-9429(1997)123:11(1041).

[18] S. Néelz, G. Pender, Benchmarking the latest generation of 2D Hydraulic Modelling Packages, 2013.