Theoretical and Empirical Researches in Urban Management
Volume 12 Issue 4 / November 2017

HYDROLOGICAL IMPACTS OF URBAN DEVELOPMENTS: MODELLING AND DECISION-MAKING CONCEPTS

Vassiliki Terezinha Galvao BOULOMYTIS
Swinburne University of Technology, Hawthorn, Melbourne VIC 3122, Australia and
State University of Campinas - UNICAMP, Av. Albert Einstein 951,Caixa Postal: 6021, Campinas, São Paulo, CEP: 13083-852, Brazil
vgalvaoboulomytis@swin.edu.au

Antonio Carlos ZUFFO
State University of Campinas - UNICAMP, Av. Albert Einstein 951, Caixa Postal: 6021, Campinas, São Paulo, CEP: 13083-852, Brazil
zuffo@fec.unicamp.br

Monzur Alam IMTEAZ
Swinburne University of Technology, Hawthorn, Melbourne VIC 3122, Australia
mimteaz@swin.edu.au

Abstract
The urbanisation of floodplains is commonly motivated due to the extensive areas with mild slopes. In non-structured regions, the lack of effective institutional frameworks for flood risk reduction is related to the unawareness of the hydrological impacts of urban developments, increasing the local vulnerability to natural hazards. It is inherent that, before the proposal of any land use and land cover (LULC) changes, the possible hydrological effects should be predicted, enhancing the possibility of mitigating the risk. However, in ungauged basins, hydrological models cannot always provide realistic outcomes, since data are scarce or non-representative. In the current study, a thorough discussion is conducted about the concepts of traditional hydrological models as well as the alternative multicriteria evaluation techniques, both used for the simulation of existing and expected LULC scenarios. The applicability and efficacy of environmental tools are also brought up to the discussion, in the context of urban planning. Accordingly, the related concepts revealed to be pertinent and feasible towards the sustainable development of urban floodplains.
Keywords: urbanisation, hydrological process, floods, modelling, decision-making.

1. INTRODUCTION

The urban sprawl preconises a wide and diffuse range of impacts. One of the main causes is the lack of integrated urban and water resource planning. The hydrological cycle for natural and urban catchments are significantly different. Vegetated areas are replaced by urban infrastructure, increasing the imperviousness, and decreasing both the transpiration and the infiltration processes (Mulligan & Crampton 2005). Runoff becomes more intense, and surfaces start pooling stormwater. A higher amount of sediments is brought to rivers, potentializing the risk of water supply contamination and the dissemination of diseases (Gaffield et al. 2003). Discharge flows are also intensified, and due to the sedimentation of river banks, the flood susceptibility increases, especially in low-lying regions, where the drainage condition is naturally problematic (Figure 1).

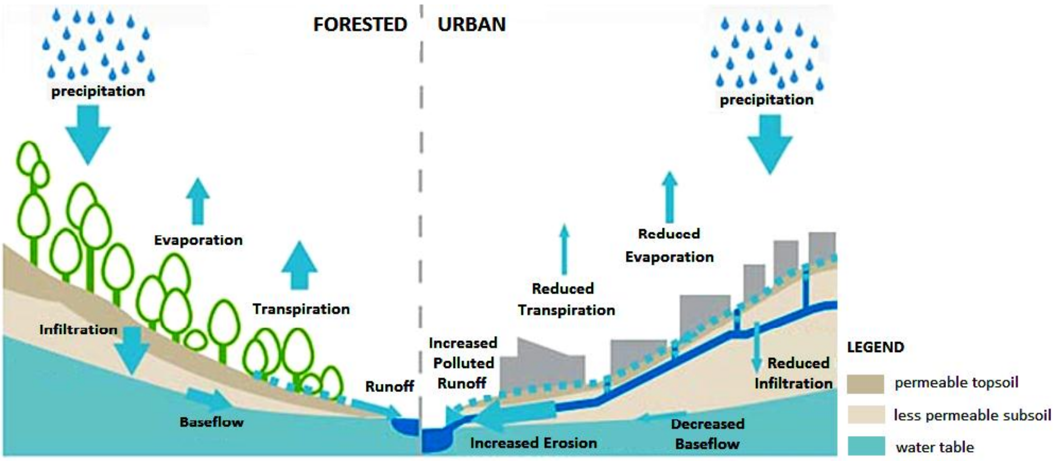

FIGURE 1 - HYDROLOGICAL CYCLE IN FORESTED AND URBANISED AREAS. SOURCE: ADAPTED FROM MELBOURNE WATER (2017).

In coastal cities, heavy rainfalls are not the only phenomena to affect the hydrological behaviour of a basin. The tide variation aggravates the impact of flooding, as the water can only be routed throughout the river when the tide level is low. Lately, the situation is reckoned to be more hazardous as a consequence of climate change and sea-level rise (Shahapure et al. 2011).

Structural measures are required to improve drainage and control floods in urban watersheds (Yfantidou & Anthopoulos 2017). Rivers are regularly straightened in order to amplify their drainage capacity, causing a sequence of inundation problems when underestimated (Shahapure et al. 2011). The combined effects of reduced sinuosity, lower roughness, lower friction in the bank, and heavier runoff make a more intense amount of water to flow in a faster pattern through the channels, contrasting from the original and "natural" river conditions (Shahapure et al. 2011).

Indeed, many non-structured regions start developing their premises following chaotic outlines, driven by economic aspects, not socially or environmentally aware of the population welfare and local vulnerability. Thus, the environmental tools tend to be ineffective without the integration of urban planning and water resource management bodies (Seller 2014).

Moreover, the sustainable development of a new urbanised area depends on a successfully integrated water resource and urban planning management, involving the micro and macro drainage design, and the structural control measures towards water contamination and floods. Knowledge about the catchment hydrological behaviour is a vital element but depends on the development of studies. For that, investments

Theoretical and Empirical Researches in Urban Management
Volume 12 Issue 4 / November 2017

are needed to raise modelling parameters and predict the hydrological impacts of forthcoming urban developments.

2. ENVIRONMENTAL TOOLS: APPLICABILITY AND EFFICACY

An effective water resources management is expected to be decentralised and represented by the public, private and community sectors (Pimentel da Silva 2010). A common purpose has to be established to keep or improve the watershed conditions for future generations, particularly concerning water quality and the population resilience and adaptation to hydrological hazard events (Pimentel da Silva 2010, United Nations International Strategy for Disaster Reduction - UNISDR 2015). Therefore, the institutionalisation of the environmental assessment tools results in a hazardous urban planning, which causes severe social and environmental vulnerability. Once the economic aspects dominate the urbanisation process, the deliberation of political actions tends to be unsatisfactory for the population welfare (Seller 2014).

The basic concepts for the Environmental Impact Assessment (EIA) rely on auditing the local environmental vulnerability, to promote alternative actions and minimise the predicted problems. The City Master Plan of every municipality is a basic environmental management tool that determines the local land use and possible activities to be implemented in each urban zone. It should always be according to the higher hierarchical legislation (i.e. State and National levels).

According to Arts et al. (2012), the effectiveness of the EIA implementation depends on the environmental considerations to be approached with the decision-makers. The level of goals might differ in case the interests of developing an area are not in the same level of the environmental vulnerability. The EIA contextual factors concern the expected results and the features of the process, decision-makers and entire context. When all the contextual factors are congregated, the governance mechanisms will also converge to the effectiveness of the EIA.

3. HYDROLOGICAL PROCESSES IN URBAN BASINS

Floodplains naturally dissipate the energy from runoff and distribute the water flow throughout the mild slope surfaces. They represent a favourable environment for plants, but also stimulate the urban development due to the mild slope conditions. As a result, the new land use and land cover (LULC) modifies the local hydrological budget, i.e. the amount of water from each hydrological cycle element (Munoz 2014).

In hydrological studies, hydrographs are used to represent the variation of the stream discharge in watersheds upon the occurrence of rainfalls (Figure 2a). The rising limb indicates how long it takes to get to the peak discharge and the lag time, the interval between the centre of mass of the precipitation and the stormflow. On smoother surfaces like pavements, the storm runoff becomes faster, reducing the lag time and making the rising limbs steeper and higher than on naturally vegetated areas (US Environmental Protection Agency - USEPA 2017) (Figure 2b). The combined facts make the watershed more susceptible to floods (Hill et al. 1998).

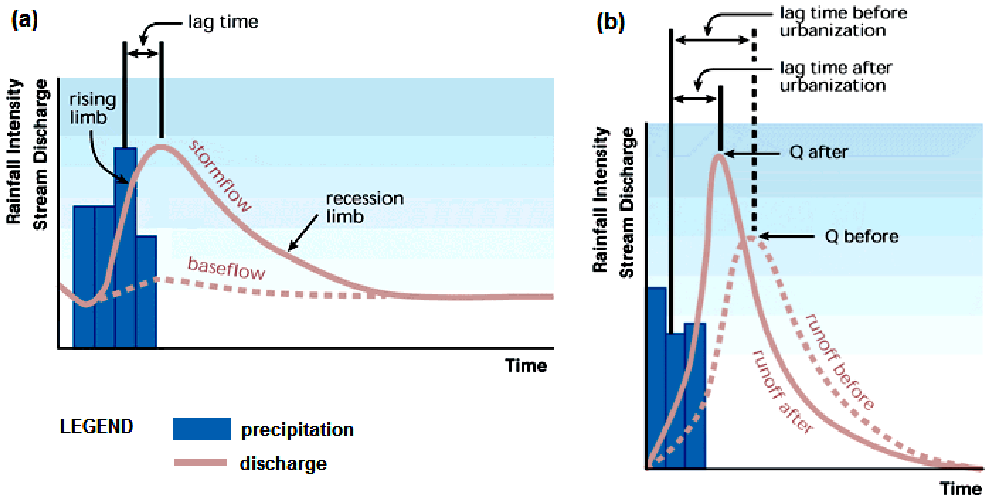

FIGURE 2 - (A) COMPONENTS OF THE STORM HYDROGRAPH. (B) URBANISATION EFFECTS ON THE STORM HYDROGRAPH. SOURCE: ADAPTED FROM USEPA (2017)

Furthermore, the concept about rainfall loss is a key element for the hydrological modelling of urbanised basins. It indicates the rainfall rate that is not converted to runoff (Hill et al. 1998). In urban areas, some physical processes that cause rainfall loss are decreased due to the LULC changes and the increase of imperviousness, e.g. the infiltration and vegetation interception. The rainfall loss only appears after a certain time counted from the beginning of the runoff, and is caused by the vegetation interception, infiltration, depression storage and transmission.

In sustainable developments, the infrastructure is developed according to the water cycle and resources available in the area, re-establishing the natural environments to improve the natural infiltration rates (Pimentel da Silva 2010). Some examples of worldwide approaches that integrate the urban land planning with the hydrological cycle are the water sensitive urban design (WSUD) used in Australia, low impact development (LID) in the United States and sustainable drainage system (SuDS) in the United Kingdom (Fletcher et al. 2015). The WSUD is defined as "the integration of urban planning with the management, protection and conservation of the urban water cycle that ensures urban water management is sensitive to natural hydrological and ecological processes" (National Water Commission - NWC 2004). The main target is to minimize the impacts on the hydrological processes due to urbanisation, notably the stormwater (Fletcher et al. 2015).

Theoretical and Empirical Researches in Urban Management
Volume 12 Issue 4 / November 2017

4. HYDROLOGICAL MODELLING IN URBAN BASINS

4.1. Conceptual models

The conceptual hydrologic models represent physical abstractions based on the implementation of mathematical and computational tools. A systematic approach of the hydrological possesses is carried out through the channel network that behaves like reservoirs. The spatial variability is not always represented in conceptual models and the rainfall/runoff is normally associated with the infiltration excess, known as the Hortonian process. However, in tropical areas, the Hortonian process is less observable than the Hewlettian process, where the runoff yield is due to the saturation excess overland flow (Descroix et al. 2007, Pimentel da Silva & Ewen 2000).

Beven and Kirkby (1979) introduced the concept of storage and contributing area of a basin, trying to minimise the dilemma of dealing with complex physically based models that requires an unfeasible amount of data. Although many conceptual models attempt to use the storage/contributing area theory, the input parameters are not directly related to the physical features of the basin (Pimentel da Silva & Ewen 2000). It results in scaling problems that can be compensated by the calibration of the models using observed reference values that refer to the dominant processes (Wu et al. 2017).

4.2. Discretisation of basins

In hydrological modelling, both vertical and horizontal hydraulic balances have to be approached to achieve more detailed outcomes, as in a basin the processes are not uniform. The vertical hydraulic balance covers the precipitation, interception, evapotranspiration, infiltration and moisture soil processes. They depend on the soil geological type and land use. Regarding the horizontal hydraulic balance, it refers to the surface runoff and depends on the drainage capacity of the area and on the topography (Collischon 2001).

Models can be concentrated or distributed, according to the way that the basin is structured. In distributed models, the basin is sub-divided or discretized into sub-basins or cells (Figure 3). The structure is defined according to the data availability, areas of interest for the study and variation of physical variables. For instance, different urban zoning (where the LULC varies), the location of gauging stations (from which inlet/outlet discharges had been previously achieved) and elevation discrepancy (e.g. plains versus mountains) are some of the possible constraints.

The discretisation of a basin plays an important role in the modelling process as it provides more detailed and realistic outcomes. Remote sensing techniques and geographic information systems (GIS) have been widely used for the discretisation of basins, by the visual interpretation of satellite imagery or aerial photograph or by the drainage extraction of digital elevation models (DEM) and digital surface models (DSM) (Bosquilia et al. 2016, Cruz et al. 2011). However, in low-lying regions where the flow is diffuse, the automatic process might impair the representation of the real topographic features (Fuller et al. 2006). In this situation, the semi-automatic approaches might enhance the final extraction results, through the participation of analysts in the correction of eventual misrepresentations.

4.3. Modelling floods in ungauged basins

Modelling ungauged basins demands a lot of efforts from hydrologists and urban planners, because data are generally scarce, requiring the implementation of alternative statistical approaches or regionalization methods (Kim & Kaluarachchi 2008).

Floods have been simulated by several methods, among which: HEC-RAS (Song et al. 2014), MIKE FLOOD (Ballesteros et al. 2011), SWAT (Baltokoski et al. 2010) and TUFLOW (Banks et al. 2014). The Hydrologic Engineering Center's (CEIWR-HEC) framework is widely used by modellers for the macro drainage planning in urban areas, predominantly the Soil Conservation Service Curve Number (SCS-CN) method, as it requires a reduced amount of parameters (Jeon et al. 2014), becoming suitable for ungauged basins.

For the flood evaluation, the HEC framework comprises the Hydrological Modelling System (HEC-HMS) and the River Analysis System (HEC-RAS) that models the hydraulics of water flow in rivers (1D) or floodplains (2D). Initially, the HEC-HMS model simulates the peak discharges of the sub-basin outlet. As the model is concentrated, more realistic outcomes are expected from detailed sub-basins derived from the basin discretization process. Later on, the HEC-HMS hydrograph is the input parameter of the HEC-RAS 2D model, which simulates the inundation boundary of the basin. An enhanced quality is achieved for the results when the model is calibrated. The calibration process might be based on the observed inundation depths. Validation methods for different events also improve the accuracy of the model (Wu et al. 2017).

4.4. Model parameterisation

The specification of the hydrological input data depends on the selected model and method run the model. In the HEC-HMS model, the SCS-CN method is very appropriate to simulate LULC scenarios in prospective urban areas. The CN is a conceptual method variable that infers the potential maximum retention of the soil after the beginning of runoff (Jeon et al. 2014). The final CN values vary from 1 to 100, from the least to the most impervious condition. Its determination is based on the combination of the LULC with the hydrological soil groups (HSG).

Remote sensing techniques and GIS have been used to derive the LULC scenarios in different spatial-temporal scales (Ilchenko & Lisogor 2016). For that, satellite imagery is classified according to the designated LULC patterns. Regarding the HSG classification, even though it was originally designed for the American soil types, Sartori et al. (2005) proposed a methodology that considered the highly weathered conditions of Brazilian soils, allocating them in the appropriate group. The soil conditions are related to their texture type, the presence of iron oxide, water table level and restrictive layers.

When estimating the peak discharge, the meteorological data play an important role in the modelling process. The accuracy of the rainfall/runoff conversion is reliant on the spatial and temporal distribution of the precipitation data. Ungauged basins normally have lack of historical data or rain gauges located in sparse areas.

The precipitation varies in three different ways: intensity, duration and frequency (IDF). The comprehensive analysis of the rain gauge historical data enables the development of IDF equations, through which the rainfall intensity can be achieved for different durations and return periods. However, these equations are not available for all rain gauges, and other statistical approaches have to be used for the hydrologic frequency analysis of rainfalls. The statistics for extreme values are very suitable for the evaluation of flood events (Yilmaz et al. 2017). Some of the probabilistic methods that refer to extreme values are the Gumbel distribution and other parent distribution functions (exponential, gamma distribution, Weibull, normal and lognormal) (Koutsoyiannis 2004).

Regarding the sparse distribution of rain gauges, the use of GIS and statistical analysis represent a good solution for the interpolation of rainfall and acquisition of more representative data (Rozante et al. 2010). The interpolators might process data from different sources and formats (vector and raster). Vector data result from rain gauges whilst raster are achieved from geostationary satellites, such as the Tropical Rainfall Measuring Mission (TRMM). The main rainfall interpolation methods that are present in literature are the inverse distance weighted (IDW), kriging and spline (Chen & Liu 2012, Dubrule 1983).

In the HEC-HMS model there are six main folders: basin (where the conversion of the rainfall/runoff is carried out through the hydrological elements of the model), meteorologic (that defines the meteorologic boundary conditions of the model), control specifications (that describes start and end time of the simulations), time-series data (where the time-series of precipitation data is inserted in the model), paired data (functional data such as cross-section profiles, unit hydrographs and storage-discharge data, depending on the available data that the modeller has for the study) and grid data (for the management of the model grid cells).

The hydrologic elements are used to assemble the separate parts of the basin, among which are the sub-basin, reach (used to convey the streamflow of the sub-basin) and junction (that combines the streamflow of the upstream area). Each element has specific parameters to describe the rainfall loss, rainfall/runoff conversion and routing flow, that are thoroughly described at the US Army Corps of Engineers - USACE (2016).

In the SCS-CN method, the main components for the sub-basin, reach and junction elements are the area, CN, lag time, and the reference discharge (which is the minimum discharge observed in the stream when there is no rainfall). In the study of Boulomytis et al. (2016), the CN variables were achieved for the simulation of the HEC-HMS model at Boulomytis et al. (2017b). The simulations were carried out for the flooding event of the 17th of March 2013 in the Juqueriquere River Basin, northern coastline of Sao Paulo, Brazil, comparing the present with the future scenario, when LULC changes are expected to occur. The paired data displayed the cross-section profile for the reach elements and the time-series data referred to the precipitation hydrograph during the event. The basin model, containing the hydrological elements and some of the components of this study, is exemplified in Figure 3.

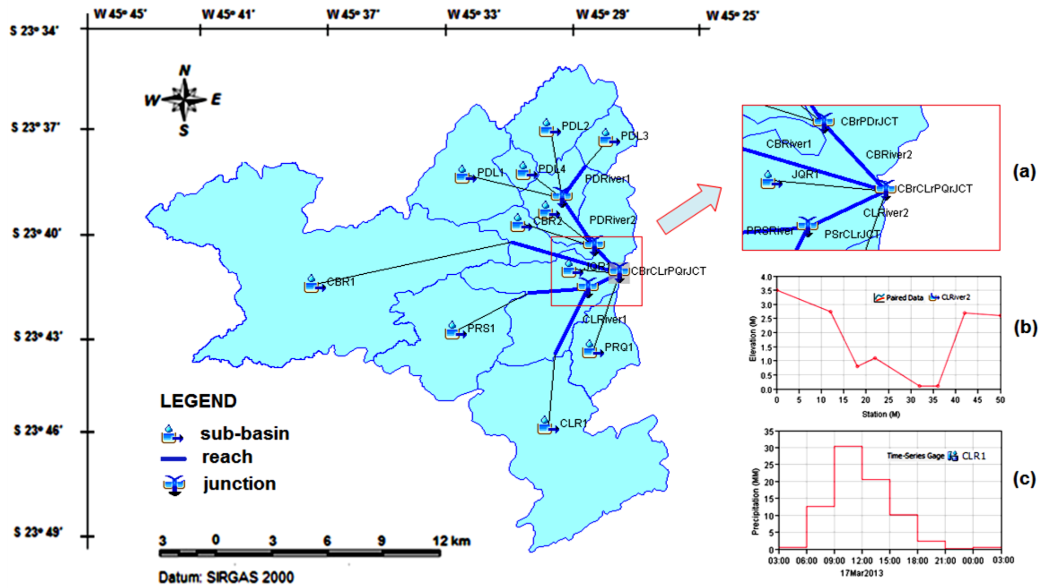

FIGURE 3 - (A) HYDROLOGICAL ELEMENTS OF A BASIN MODEL. (B) PAIRED-DATA: THE CROSS-SECTION OF THE CLARO RIVER REACH (CLRIVER2). (C) TIME-SERIES DATA: PRECIPITATION HYDROGRAPH OF THE CLARO RIVER SUB-BASIN (CLR1).

After deriving the outcomes of the hydrological modelling, the HEC-RAS may be applied to simulate the water level of rivers or inundation depths of floodplains. At first, it is very important to calibrate the Manning's roughness coefficient, which is one of the parameters for the hydraulic modelling. When only a few observed stage and discharges are available, the HEC-RAS 1D can still be used for the calibration of the Manning's roughness coefficient. Many examples of this calibration are available in the literature (Boulomytis et al. 2017a, Song et al. 2014). These coefficients vary significantly, and even if they are already provided, the outcome of the flood simulation becomes more realistic after their calibration.

Subsequently, the flood simulations in the different LULC scenarios are possible to be carried out in the HEC-RAS 2D model. The accuracy of this model depends fundamentally on the DEM or topographic elevation data, as it relies on the terrain raster map initially built in the RAS mapper. A 2D flow area is also drawn around the plains to be modelled, aiming to minimise data processing time and computational effort. The time-series peak flow of the sub-basin outlets (previously generated by the HEC-HMS model) are attributed to the inlet flow of the drawn floodplains. The flow conditions might be steady, unsteady (simulation of floods) or quasi-unsteady (for sediment analysis). For the floodplains of Boulomytis et al. (2017b), the HEC-HAS 2D application is illustrated in Figure 4. It shows the terrain map of the floodplains (derived from an elevation model), the drawn 2D flow area and the simulated inundation depth for the present LULC scenario (for the event of 17th of March 2013).

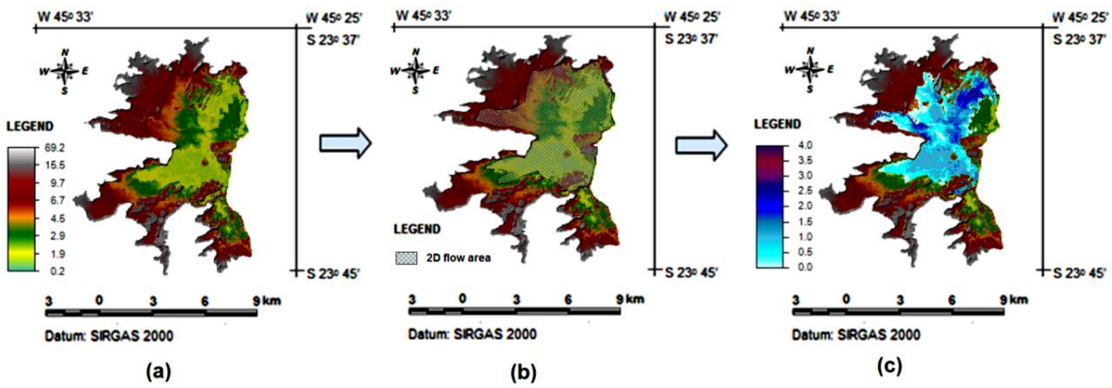

FIGURE 4 - HEC-RAS 2D: (A) TERRAIN MODEL. (B) 2D FLOW AREA. (C) FLOOD SIMULATION.

5. MULTICRITERIA EVALUATION METHODS

Hydraulic models, such as the described HEC-RAS 2D, enable the simulation of different scenarios, but may provide incoherent results when the input data are not representative, or when calibration and validation procedures are not feasible. Alternative approaches like the multicriteria evaluation (MCE) techniques have been widely used by policy makers and urban planners. They were developed to improve the efficiency of the decision-making (DM) activity by aggregating a set of criteria for the evaluation of the best alternative (Zuffo et al. 2002, Yahaya et al. 2010).

Many flood investigations using MCE techniques are found in literature, analysing what could not be treated by the traditional methods (Horita et al. 2015, Yahaya et al. 2010). In some studies, a combination of the MCE techniques and hydraulic models is carried out for calibration purposes, improving the final quality of the outcomes (Yang et al. 2011).

5.1. Historical development

Last century, the MCE applied the multiple programming approaches to solving a problem from a goal-based DM (Zuffo et al. 2002). The American school aimed to find the best solution for the outcome of a DM process referred to as multicriteria decision-making (MCDM). For this reason, the concept was based on the optimization of the objective functions instead of the problem structural base (Korhonen et al. 1992).

Meanwhile, the European school proposed a new concept, targeting a better-committed solution for a new multicriteria method as an aid towards the DM, designated as multicriteria decision analysis (MCDA) (Zopounidis & Doumpos 2002). For that, the problem was not treated separately. Each observer developed, structured and evaluated the problem according to its own system of values. The objective and subjective elements could be aggregated, depending on their relationship. Thus, the decision could be modified along the process, when the decision-maker got more knowledge about the specific problem (Zuffo et al. 2002).

Since then, several multicriteria methods have been developed and used, following the structure recommended by different authors (Zopounidis & Doumpos 2002). These methods might be based on a single or multiple objective functions. For the multiple objective functions, Cohon & Marks (1975) proposed a classification according to the technique used by the decision maker to solve a problem (Table 1).

TABLE 1 - CLASSIFICATION OF THE MULTIPLE OBJECTIVE FUNCTIONS.

Method	Technique
Weighted Product Model (WPM), Weighted Sum Model (WSM), and Multiple Objective Linear Programming (MOLP)	Generation of a set of non-dominated solutions, without any personal preferences. A set of non-dominated solutions is generated for the vector of objective functions, where only the physical constraints of the problem are considered.
Elimination and Choice Translating Reality (ELECTRE), Preference Ranking Organization Method of Enrichment Evaluation (PROMETHEE), and Analytical Hierarchy Process (AHP)	Prior articulation of preferences. The opinion of the decision maker is requested before the DM, regarding possible changes in the objective values.
Step-Method and *Compromise Programming (CP)*	Progressive articulation of preferences in order to resolve conflicts among the decision makers or conflicting objectives. Once a solution is reached, the decision maker is asked if the desired level to set goals was reached. If not, the problem can be modified until it is the best solution for the problem.

The assortment of procedures and structural techniques should be an aid to the decision-maker. Independent on the school trend, the efficient DM depends on the appropriate statement of the decision problem and reliable definition of techniques for the construction of criteria (Zopounidis & Doumpos 2002).

5.2. Framework

According to Yang et al (2011), the general MCE framework is divided into the following components: scenario definition, problem structuring, criteria attribution, criteria weight, decision-making, GIS-based

Theoretical and Empirical Researches in Urban Management
Volume 12 Issue 4 / November 2017

criteria, likelihood maps, validation, sensitivity analysis and scenario appraisal (Figure 5). In the perspective of flood evaluation, both the non-urbanised and urbanised scenarios should be evaluated, according to the predicted LULC changes. The scenarios must be related to the problem structure. So, the analysis of flood susceptibility is carried out in the respective scenario.

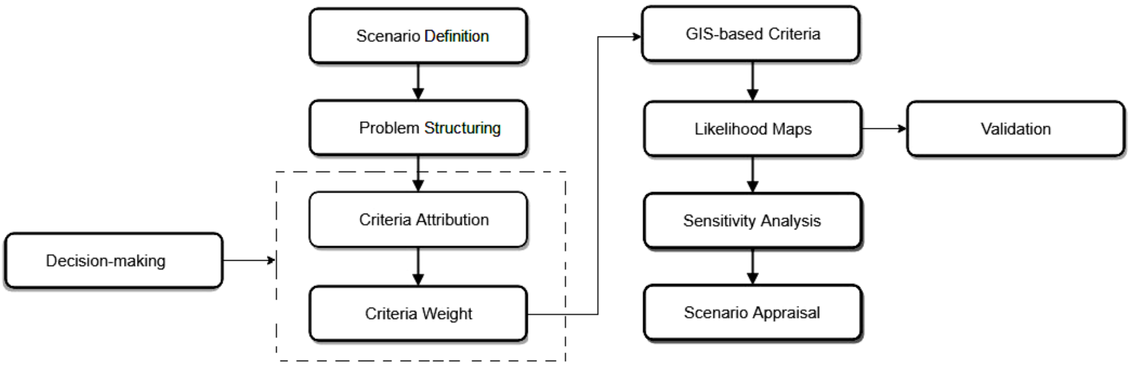

FIGURE 5 - GENERAL PROCEDURES FOR THE MCE TECHNIQUES.

The attribution of criteria can be based on a survey or prior knowledge of the problem thereof. The Delphi-method is an expert-based survey that has been used by policy planners for sustainable development approaches (Garcia-Melon et al. 2012). The main advantage of the method is that the survey is anonymous and there is no respondent bias, i.e. one decision maker does not influence the others. The disadvantage is that the score difference between two criteria is reduced after the statistical treatment of the data, which excludes all outliers.

One of the MCDA techniques is the AHP (Saaty 1977), mostly applied for the simplification of complex problems. It is based on the pairwise comparison of the criteria matrix that is further in a hierarchical multilevel structure (Shin et al. 2013). The consistency analysis is the major advantage of the AHP technique. All the criteria are scored according to their level of importance that is indicated by a judgement scale. The linear scale (Saaty 1977) is the most widespread. However, others have been also studied lately, each one with the respective mathematical description (Ishizaka & Labib 2011), among which are: Power, Root Square, Geometric, Inverse linear, Asymptotical, Balanced and Logarithmic. The selection of the appropriate judgement scale is pertinent because it interferes in the final criteria score (Ishizaka & Labib 2011).

The implementation of the criteria in the GIS environment is related the spatial parameterisation of the MCDA model. The association of the criteria in a GIS-basis results in a likelihood map, where the relevance of each criterion is materialised. These maps cannot always be validated, because of the lack of reference variables, which is common in ungauged basins. Nonetheless, a validated model provides more trustworthy outcomes, and gain more importance to be treated by policymakers.

Regarding the sensitivity analysis (SA), it is a means of identifying the effects of changes in the input criteria (Yang et al. 2011). The SA can be implemented in the criteria ranking phase or criteria values, before the final scenario appraisal. In this stage, the urban planners can evaluate the different scenarios and achieve the best solution for their initial problem. When the defined problem is to determine the most susceptible areas to flood, the final recommendations will be to decrease the criteria values that mostly affect the likelihood of floods. In case the criteria values are not possible to be varied (i.e. when they are natural or physical characteristics of the basin), other solutions might be proposed, based on the achieved results and the enhanced perception of the local vulnerability, which might even include the design of sustainable LULC changes.

6. CONCLUSIONS

Even though some areas are naturally vulnerable to hazards, they are still favourable to be urbanised. When the interest of developing the environmental assessment tools is institutionalised, the social and environmental consolidated risk is disregarded, making the tools inefficient for urban planning.

The hydrological processes alter significantly from the forested to the urbanised (and impervious) areas. Conversely, the magnitude of the effects can only be predicted based on the accurate modelling of the basin, which depends on the availability of representative input data. In ungauged basins, it is very challenging to apply the traditional hydrological techniques. The SCS-CN method used in the HEC framework seems to be suitable for the simulation of LULC changes in prospective urban developments, due to the limited parameters necessary to run the models. However, the CN is not a physical parameter through which the infiltration rate might be inferred. Thus, the calibration and validation become fundamental procedures for the accuracy of the rainfall/runoff conversion.

To conclude with, alternative approaches like the MCE techniques show that it is possible to assess the risk in a feasible manner, even when limited data are available. Therefore, the prediction of hydrological impacts has to precede the design of LULC changes, aiming the development of a sustainable urbanisation process.

ACKNOWLEDGMENTS

We gratefully acknowledge UNICAMP and the Brazilian National Council for the Improvement of Higher Education (CAPES) for the study support, and the Australian Government for the Research Training Program (RTP) Fees Offset Scholarship at Swinburne University of Technology.

REFERENCES

Arts, J., Runhaar, H.A., Fischer, T B., Jha-Thakur, U., Van Laerhoven, F., Driessen, P.P., & Onyango, V. (2012). The effectiveness of EIA as an instrument for environmental governance: reflecting on 25 years of EIA practice in the Netherlands and the UK. *Journal of Environmental Assessment Policy and Management*, 14(04), 1-41.

Ballesteros, J., Bodoque, J., Diez-Herrero, A., Sanchez-Silva, M., & Stoffel, M. (2011). Calibration of floodplain roughness and estimation of flood discharge based on tree-ring evidence and hydraulic modelling. *Journal of Hydrology*, 45 (3), 103-115.

Baltokoski, V., Tavares, M.H.F., Machado, R.E., & Oliveira, M.D. (2010). Calibracao de modelo para a simulacao de vazao e de fosforo total nas sub-bacias dos rios Conrado e Pinheiro–Pato Branco (PR). *Revista Brasileira de Ciencia do Solo*, 34 (1), 253-261.

Banks, J.C., Camp, J.V., & Abkowitz, M.D. (2014). Adaptation planning for floods: a review of available tools. *Natural hazards*, 70(2), 1327-1337.

Beven, K.J., & Kirkby, M.J. (1979). A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. *Hydrological Sciences Journal*, 24(1), 43-69.

Bosquilia, R.W.D., Fiorio, P.R., Duarte, S.N., Mingoti, R., & Zocchi, S.S. (2016). Diferentes produtos de sensoriamento remoto no mapeamento visual de drenagens e nascentes na Microbacia Hidrografica do Ceveiro. *Revista de Agricultura*, 91(1), 1-16.

Boulomytis, V.T.G., Imteaz, M.A., Zuffo, A.C., & Alves, C.D. (2016). Analysis of the urbanisation effects on the increase of flood susceptibility in coastal areas. *Theoretical and Empirical Researches in Urban Management*, 11(4), 30-45.

Boulomytis, V.T.G., Zuffo, A. C., Dalfre Filho, J.G., & Imteaz, M.A. (2017a). Estimation and calibration of Manning's roughness coefficients for ungauged watersheds on coastal floodplains. *International Journal of River Basin Management*, 15(2), 199-206.

Boulomytis, V.T.G., Zuffo, A.C., Imteaz, M.A., & Herrera, M.A.C. (2017b). *The effectiveness of the CN method in areas with saturated soil conditions.* Paper presented at 22nd International Congress on Modelling and Simulation (MODSIM 2017), Hobart, Tasmania, Australia.

Chen, F. W. and Liu, C. W. (2012). Estimation of the spatial rainfall distribution using inverse distance weighting (IDW) in the middle of Taiwan. *Paddy and Water Environment*, 10(3), 209-222.

Cohon, J.L., Marks, D.H. (1975). A review and evaluation of multiobjective programming techniques. *Water Resources Research*, 11(2), 208-220.

Collischonn, W. (2001). *Simulacao hidrologica de Grandes Bacias*. (PhD Thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil) 2001.

Cruz, C.B.M., Barros, R.S., Cardoso, P.V., Reis, R.B., Rosario, L.S., Barbosa, S.S., Rabaco, & L.M.L. Lourenco, J.S.Q. (2011). *Avaliacao da exatidao planialtimetrica dos modelos digitais de superficie (MDS) e do terreno (MDT) obtidos atraves do LIDAR.* Paper presented at. XV Simposio Brasileiro de Sensoriamento Remoto (SBSR 2011), Curitiba, PR, Brazil.

Descroix, L., Viramontes, D., Estrada, J., Barrios, J.L.G., & Asseline, J. (2007). Investigating the spatial and temporal boundaries of Hortonian and Hewlettian runoff in Northern Mexico. *Journal of hydrology*, 346(3), 144-158.

Dubrule, O. (1983). Two methods with different objectives: splines and kriging. *Mathematical Geology*, 15(2), 245-257.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., ... & Mikkelsen, P. S. (2015). SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525-542.

Fuller, L.M., Morgan T.R., Aichele, S.S. (2006). *Wetland Delineation with IKONOS High-Resolution Satellite Imagery*, U.S. Geological Survey Scientific Investigations Report 2006-5051.

Gaffield, S.J., Goo, R.L., Richards, L.A., & Jackson, R.J. (2003). Public health effects of inadequately managed stormwater runoff. *American Journal of Public Health*, 93(9), 1527-1533.

Garcia-Melon, M., Gomez-Navarro, T., & Acuna-Dutra, S. (2012). A combined ANP-Delphi approach to evaluate sustainable tourism. *Environmental Impact Assessment Review*, 34, 41-50.

Hill, P., Mein, R., & Siriwardena, L. (1998*). How much rainfall becomes runoff? Loss modelling for flood estimation* (Industry Report 98/5). Melbourne, Australia: Cooperative Research Centre for Catchment Hydrology.

Ilchenko, K., & Lisogor, A. (2016). Sustainable Development Modeling for Municipalities. Theoretical *and Empirical Researches in Urban Management*, 11(1), 77-85.

Ishizaka, A., & Labib, A. (2011). Review of the main developments in the analytic hierarchy process. *Expert Systems with Applications*, 38(11), 14336-14345.

Jeon, J.H., Lim, K.J., & Engel, B A. (2014). Regional calibration of SCS-CN L-THIA model: application for ungauged basins. *Water*, 6(5), 1339-1359.

Kim, U., & Kaluarachchi, J.J. (2008). Application of parameter estimation and regionalization methodologies to ungauged basins of the Upper Blue Nile River Basin, Ethiopia. *Journal of Hydrology*, 362(1), 39-56.

Korhonen, P., Moskowitz, H., & Wallenius, J. (1992). Multiple criteria decision support – A review. *European Journal of Operational Research*, 63, p.361-375, 1992.

Koutsoyiannis, D. (2004). Statistics of extremes and estimation of extreme rainfall: I. Theoretical investigation/Statistiques de valeurs extremes et estimation de precipitations extremes: I. Recherche theorique. *Hydrological sciences journal*, 49(4).

Melbourne Water (n.d.). *Introduction to WSUD.* Retrieved September 12, 2017, from: https://www.melbournewater.com.au/planning-and-building/stormwater-management/

Mulligan, G.F., & Crampton, J.P. (2005). Population growth in the world's largest cities. *Cities*, 22(5), 365-380.

Munoz, V.A (2014). *Espacializacao do indice relevo-elevacao (E) na bacia do rio Itajai a partir de MDE* (PhD Thesis, Instituto Nacional de Pesquisas Espaciais, Sao Jose dos Campos, SP, Brazil) 2014.

NWC (2004). *Intergovernmental agreement on a National Water Initiative*. Commonwealth of Australia and the Governments of NSW, VIC, QLD, SA, ACT and NT.

Pimentel da Silva, L. (2010). Integracao do planejamento urbano e de recursos hidricos pela sustentabilidade ambiental. *Chao Urbano*, 2010, 1-4.

Pimentel da Silva, L., & Ewen, J. (2000). Modelagem hidrologica para grandes bacias hidrograficas: a necessidade de novas metodologias. *Revista Brasileira de Recursos Hidricos*, Brasil, 5, 81-92.

Rozante, J.R., & Moreira, D.S. (2010). Combining TRMM and surface observation precipitation: technique and validation over South America. *Weather and Forecasting*, 25, 885-894.

Saaty, T.L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, 15(3), 234-281.

Sartori, A., Lombardi Neto, F., & Genovez, A.M. (2005). Classificacao hidrologica de solos brasileiros para a estimativa da chuva excedente com o metodo do Servico de Conservacao do Solo dos Estados Unidos Parte 1: Classificacao. *Revista Brasileira de Recursos Hidricos*, 10(4), 05-18.

Seller, E.P. (2014). La Mediacion como servicio publico de la administracion local en las sociedades relacionales contemporaneas. *Revista Brasileira de Gestao e Desenvolvimento Regional*. 10(1), 3-27.

Shahapure, S.S., Eldho, T.I., & Rao, E.P. (2011). Flood simulation in an urban catchment of Navi Mumbai City with detention pond and tidal effects using FEM, GIS, and remote sensing. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 137(6), 286-299.

Shin, Y.B., Lee, S., Chun, S.G., & Chung, D. (2013). A critical review of popular multicriteria decision-making methodologies. *Issues in Information Systems*, 14(1), 358-365.

Song, S., Schmalz, B., & Fohrer, N. (2014). Simulation and comparison of stream power in-channel and on the floodplain in a German lowland area. *Journal of Hydrology and Hydromechanics*, 62(2), 133-144.

United Nations International Strategy for Disaster Reduction - UNISDR (2015). *Sendai Framework for Disaster Risk Reduction.* Retrieved August 10, 2017, from http://www.unisdr.org/we/coordinate/sendai-framework/

US Army Corps of Engineers - USACE (2016*). HEC-HMS User's Manual, v.4.2* , Davic, CA: Hydrologic Engineering Center.

US Environmental Protection Agency - USEPA (2017). *Stream Corridor Structure*. Retrieved September 03, 2017, from: https://cfpub.epa.gov/watertrain/

Wu, Q., Liu, S., Cai, Y., Li, X., & Jiang, Y. (2017). Improvement of hydrological model calibration by selecting multiple parameter ranges. *Hydrology and Earth System Sciences*, 21(1), 393-407.

Yahaya, S., Ahmad, N., & Abdalla, R.F. (2010). Multicriteria analysis for flood vulnerable areas in Hadejia-Jama'are River basin, Nigeria. *European Journal of Scientific Research*, 42(1), 71-83.

Yang, M., Qian, X., Zhang, Y., Sheng, J., Shen, D., & Ge, Y. (2011). Spatial multicriteria decision analysis of flood risks in aging-dam management in China: A framework and case study. *International Journal of Environmental Research and Public Health*, 8(5), 1368-1387.

Yfantidou, G., & Anthopoulos, P. (2017). Designing of outdoor green recreational parks. *Theoretical & Empirical Researches in Urban Management,* 12(2). 5-18.

Yilmaz, A.G., Imteaz, M.A., & Perera, B.J.C. (2017). Investigation of non-stationarity of extreme rainfalls and spatial variability of rainfall intensity–frequency–duration relationships: a case study of Victoria, Australia. *International Journal of Climatology*, 37(1), 430-442.

Zopounidis, C., & Doumpos, M. (2002). Multicriteria classification and sorting methods: a literature review. *European Journal of Operational Research*, 138(2), 229-246.

Zuffo, A.C., Reis, L.F.R., Santos, R.F., & Chaudhry, F.H. (2002). Aplicacao de Metodos Multicriteriais ao Planejamento de Recursos Hidricos. *Revista Brasileira de Recursos Hidricos*, 7(1), 81-102.