Supporting urban development master plans by hydraulic invariance concept: the case study of Acquicella catchment

Soutenir les plans directeurs de développement urbain par le concept d'invariance hydraulique. L'étude de cas du bassin versant d'Acquicella

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RÉSUMÉ

Comprendre les impacts potentiels du développement urbain sur le système de drainage est une question cruciale, dès les premières étapes des plans directeurs de développement urbain (UDMP).
Cet article applique le concept de l'Invariance Hydraulique (HI) à une étude de cas concernant un bassin versant dans la partie sud de la ville de Catane, en Italie. Une comparaison entre les scénarios des bassins avant et après le développement du rejet des eaux pluviales est présentée. La dernière faisant référence à la proposition de refonte du plan stratégique de développement urbain, récemment réalisé pour la ville. Les simulations de scénarios ont été exécutées à l'aide du modèle de SWMM fourni par l'EPA. L'étude montre la nécessité d'un examen attentif de l'HI dans les actions de planification de l'utilisation des terres. En particulier, un ensemble de limitations du flux à attribuer à des points de développement (c'est à dire des zones de transformations conçues par l'UDMP) ont été déterminés, sur la base de la réalisation de l'invariance hydraulique à l'échelle du sous bassin versant pour plusieurs périodes de retour des eaux pluviales. Les critères retenus pour attribuer des restrictions de sortie ont été choisis sur la base de l'augmentation des sorties des flux des eaux pluviales sortant des mêmes points de développement.

ABSTRACT

Understanding potential impacts of urban development on storm water drainage modifications is a crucial issue since early design stages of urban development master plans (UDMPs). This paper applies the concept of Hydraulic Invariance (HI) to a case study catchment in the southern part of the City of Catania, Italy. Comparison between pre- and post-development catchment storm-water release scenarios is presented. The latter referring to the UDMP's re-design proposal, recently carried out for the city. Simulations of scenarios were run using the SWMM model provided by EPA. The study shows the need for careful consideration of HI in land use planning actions. In particular, a set of flow release restrictions to assign to clusters of development (i.e. areas of transformations designed by the UDMP) were determined, based on the achievement of hydraulic invariance at the sub-catchment scale for different return period of the storm-water event. The criterion adopted to allocate release restrictions has been chosen on the base of the increase of storm-water release flows discharged from the same clusters of development.

KEYWORDS

Hydraulic invariance, land use master plans, release restrictions, strategic planning, urban water planning

1 INTRODUCTION

Under conditions of urbanization processes responsible for altering natural flow patterns in terms of both runoff volumes and peaks (Chocat et al., 2001; Woods-Ballard et al., 2007; Fletcher et al., 2012), conventional storm water systems are pushed beyond their drainage capacity and may lead to more frequent and intense floods (Elliot and Trowsdale, 2007; Maksimović et al., 2009; Hammond et al., 2015).

Spatial planning associated to Urban Development Master Plans (UDMPs) and related actions influences catchment hydrologic response in depth. Then, understanding potential effects of urban development on storm water drainage asset modification is a crucial issue since early design stages of UDMPs (Miguez, 2015). Specifically, several papers have stressed the importance of hydrologic/hydraulic analysis as basic tool to support city planners into setup of sustainable urban development (Kleidorfer et al. 2013, Hellmers et al. 2013, Willuweit et al. 2015).

Control of flow releases from sub-catchments has become a serious factor of concern and the focus of several urban policies approaches in numerous countries. As storm water management strategy, it involves a number of retention, infiltration, and runoff reduction measures (Guo and Urbonas, 2009). In particular, regional water agencies in Italy are increasingly promoting directives addressed to the concept of “hydraulic invariance” (HI), namely the condition for peak flow release from transformed areas to remain unvaried before and after land transformation.

The adoption of this concept requires to set appropriate mitigation/compensatory measures at the catchment scale and to define criteria for allocation of burdens due to excess storm-water runoff and water quality decay in urban areas (Parikh et al., 2012). In this regard, one way to proceed is to charge the developer with the responsibility for the impacts due to development (Extended Producer Responsibility - EPR principle).

By the mean of a case study catchment within the city of Catania in Sicily, Italy, this paper shows the main results of the hydrologic/hydraulic analysis aimed at assessing the impact of the city development master plan provisions in terms of increase of flow peak releases from urban catchments concerned by transformations of land uses.

The adoption of HI principle is applied in order to implement storm water control measures into UDMPs. A set of flow release restrictions were determined and assigned to areas of transformation based on comparison between pre- and post-development catchment storm-water release scenarios. Simulation of scenarios was carried out using EPA Storm Water Management Model (SWMM) (Rossman, 2004) for a number of design storm events of selected return periods.

2 CASE STUDY

Before urbanization processes the Acquicella catchment (Figure 1) was basically a rural basin with an almost natural drainage system made up of the Acquicella torrent with a number of smaller ephemeral tributary branches, responsible for the alteration of the catchment’s physical features. After development in the ‘60s – ‘80s, the original torrents have been largely replaced by artificial channels. Today, such channels receive also combined overflows from adjacent sewers. The main channel originates in the southern area of the settlement of Misterbianco. It flows in direction NW-SE proceeding through various neighborhoods of the municipality before flowing into the sea, south of the city harbor. It is about 9,0 km long and shows different shape configurations. The larger tributary branch (the Carcaci torrent) is about 4,1 km long and flows into the Acquicella channel in the SE part of the catchment. Five large sewers collect storm water from urbanised areas of the catchment, with final outlet into the main torrent system.

The current flood risk status is analysed in the Hydro-geological Asset Plan provided by the Sicilian Regional Department of Environment: according to flood risk maps provided, limited areas in the catchment would result affected by the high level of risk, thus prone to flooding.

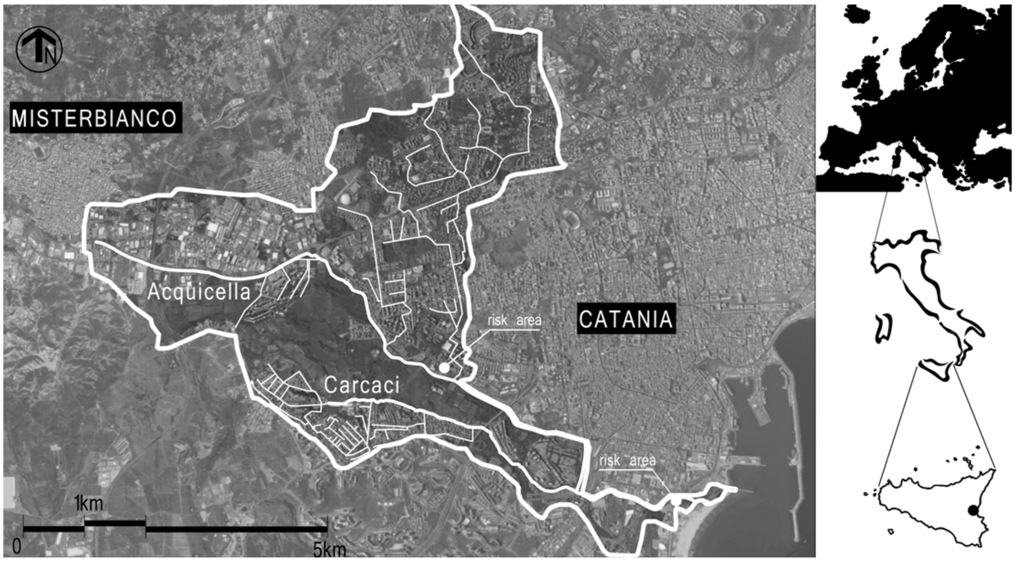

Figure 1-The Acquicella catchment and its drainage network Legend for tables above the object, centred

The study catchment is concerned by proposals of the new urban development master plan (UDMP) whose preliminary study was committed by Catania Municipality to the University.

Among planning objectives and design schemes of the new UDMP one cluster of intervention is of major interest. It is the cluster of the “city to transform”, namely urban areas showing potentialities for urban quality increase through integration / renewal of existing fabric. Areas belonging to this cluster are characterized by potentially incisive modifications in terms of urban functions and provision of services. In particular, the UMDP identifies specific zones characterized by high degrees of transformability and refers they as Resource Zones (RZs) (Figure 2). Each RZ is designed as a mixed-use area and always includes land parcels for residential/commercial/directional functions or for activities related to public interest, green areas, roads and parking areas (Martinico et al., 2014). Eleven RZs fully or partly fall within the boundaries of the Acquicella catchment and are mainly localized in its mid-downstream portion.

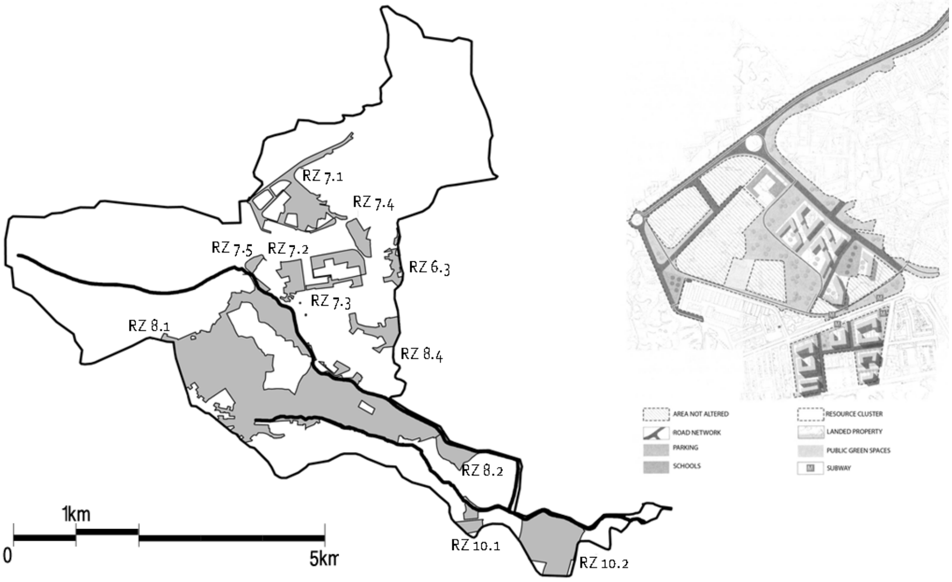

Figure 2-The ‘Resource Zones’ falling within the Acquicella catchment area as identified by the LUMP proposal. At the top-right, RZ 7.1 in detail as an example

3 METHOD

The applied methodology is based on three main steps:

- Step 1-Simulation scenario and HI indicator selection
- Step 2-Model selection
- Step 3-Definition of catchment release restrictions

3.1 Simulation scenario and HI indicator selection

In order to evaluate the catchment hydrologic response to impacts of UDMP proposals, the analysis required to identify simulation scenarios to compare: the first scenario is representative of the catchment in its current condition, while the second scenario represents the catchment after that transformations considered by the UMDP have occurred. As the HI concept requires maintaining actual flow peaks unvaried in the catchment, the peak flow ratio was adopted as resilience indicator for the purpose of the present investigation in order to evaluate how close the post-development scenario was to the required hydraulic invariance condition:

$$I_{HI} = \frac{Q_{p2}}{Q_{p1}} - 1 \quad (1)$$

where Q_{p2} is the value of flow peak released from the catchment in the post-development scenario, and Q_{p1} is the value of the flow peak released in the pre-development scenario.

3.2 Model selection

The catchment hydrologic response and the proximity to the HI principle were analysed by a simplified approach, coherently with the planning scale and its required level of representation. The EPA Storm Water Management Model (SWMM) hydrologic module was used to simulate chosen scenarios.

The catchment was split into a number of sub-catchments, each identified in correspondence to the principal tributary branches of the main torrent. In addition, the outlet section of the whole catchment was considered for a global evaluations.

Characteristics of the catchment for model implementation were deduced by the available cartography, land use analysis and thematic maps provided by previous preliminary studies. Additional input parameters for each sub-catchment included slope, overland flow width, Manning’s roughness coefficient for overland flow on both pervious (n_{p}) and impervious surfaces(n_{imp}), and depths of depression storage (d_{p}, d_{imp}). Infiltration loss was modeled using the Curve Number (CN) infiltration method (U.S. SCS, 1972). In order to compare scenarios, the appropriate imperviousness percentage value and CN value were assigned to sub-catchments in the post-development scenario based on the way sub-areas of each sub-catchment were affected by transformations in the related RZs. In particular, the layer of sub-areas (i.e. homogeneous portions of sub-catchment in terms of land use destinations) was matched with layer of RZs (i.e. homogeneous portions of RZ in terms of urban destinations) for each considered sub-catchment.

Runoff from sub-catchments was simulated as overland flow only, thus neglecting flow propagation in the system of channels.

Intensity-Duration-Frequency curves, which were used for the setup of design storm events, were derived for a range of return periods from data provided by the Sicilian Regional Department of Water and Waste.

3.3 Definition of catchment release restrictions

Regulatory measures to counterbalance peak runoff increase due to land transformations may find practical explication by introducing flow release restrictions in the catchment. Available examples of application of release restrictions have been developed with reference to the parcel scale (Parikh et al., 2005). The adoption of the parcel scale-based approach may be appropriate for detailed scale analysis concerning the setup of suitable tools for municipalities to burden single owners. Contrarily, such an approach is not feasible for the level of the analysis adopted in this paper because the parcel scale is not appropriate for evaluations at the planning level. Then, penalties (in terms of a single release restrictions) due to increased storm-water flows are assigned to RZs responsible for land transformations as a whole, in order to assure hydraulic invariance at the sub-catchment level. Procedurally, for each sub-catchment, excess flow peak (peak difference between pre- and post-development scenarios) is distributed to RZs (included in the sub-catchment) based on their contribution to the generation of the excess flow peak. This means that the RZ is the reference unit for applying distribution/allocation mechanisms for release restrictions.

4 APPLICATION TO THE CASE STUDY CATCHMENT

4.1 Preliminary evaluation of catchment parameters

The Aquicella catchment was divided in five sub-catchments. Four of them were identified in correspondence to relevant points of the main torrent system that are inlets of important tributary branches (section S1-S4). The remaining catchment correspond to the outlet section of the Acquicella (section S5). Details about sub-catchment characteristics used as input for SWMM simulations are reported in Table 1. Design rain events for simulation of both scenarios were determined using the Chicago synthetic hyetograph (Keifer and Chu, 1957) associated to six return periods (2, 5, 10, 20, 50, and 100 years) relevant for urban flood risk analysis.

The pre-development scenario as the reference condition for the comparative analysis was chosen after preliminary investigations aimed at verification of hydraulic compatibility of sub-catchment outlet sections with calculated flow peak releases. The evaluation of curve numbers to assign to each sub-catchment was based on land use analysis and soil type analysis. As the post development scenario is concerned, urban destinations were identified based on the UMDP proposal. Resulting values of CN and imperviousness ratio assigned to each sub-catchment for both pre- and post-development scenarios are summarized in Table 1.

Table 1- Characteristics of the identified sub-catchments

				Pre- development scenario		*Post- development scenario*	
Sub-catchment	**Surface area** *[ha]*	**Slope** *[%]*	**Width** *[m]*	**Imperviousness** *[%]*	**CN**	**Imperviousness** *[%]*	**CN**
S1	397.40	2.67	1156	51.21	88	51.34	88
S2	86.94	2.80	383	70.68	89	74.44	90
S3	573.45	3.30	969	50.19	86	52.86	87
S4	228.31	3.00	478	46.21	84	50.17	86
S5	1500.20	2.60	1540	52.62	85	54.97	87

n_p *[s/m^{1/3}]*	n_{imp} *[s/m^{1/3}]*	d_p *[mm]*	d_{imp} *[mm]*
0.1	0.15	5	2

5 RESULTS AND DISCUSSIONS

SWMM-based simulation analysis provided for peak flow values at the outlet nodes of each sub-catchment and allows for a comprehensive comparison of the two scenarios.

Figure 3 sums up simulated peak flow releases for unit sub-catchment area (l/s/ha) for all the considered return periods of the storm flow event and for both pre-development (Figure 3a) and post-development (Figure 3b) scenarios. Results would confirm the general sustainability of overall transformations associated to the urban development master plan proposal as they would globally not alter the hydrology in the whole catchment in a significant way. However, going into details of Figure 3, results reveal sub-catchments to be affected to various extent by impact of land transformation. As expected, differences depend on variations of CN values and imperviousness along with sub-catchments' peculiar site characteristics.

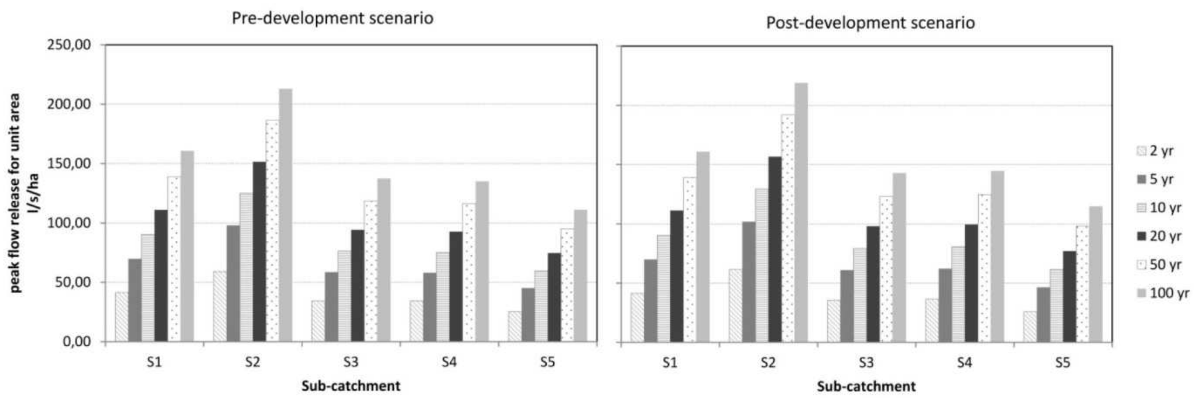

Figure 3-Sub-catchment peak flow releases for unit sub-catchment area for pre-development scenario and post-development scenario

Simulation results show that a set of flow release restrictions for the reduction of flow peaks should be proposed as complementary tool to the UDMP in order to achieve hydraulic invariance in all the sub-catchments. Figure 4 shows flow release restrictions assigned to RZs involved in the catchment. As expected, required restrictions increase as the return period of the design event increases. Results show restriction values in the range 0,3-16,2 l/s/ha assigned to all RZs for the lower return period (2 year). As far as mitigation actions are concerned, compliance with this range of values would open to implementation of source control measures like green infrastructure options (Miguez et al., 2009). Instead, results for higher return periods point out the need for higher release restriction values (up to about 70 l/s/ha for 100 years return period) to all RZs to achieve HI. According to literature, in this case, combination of source control measure with concentrated detention based techniques would probably result necessary for various RZs.

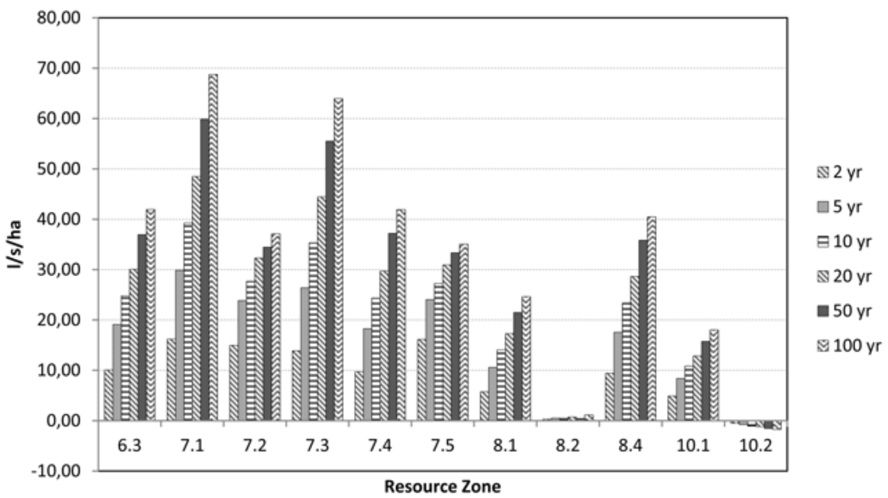

Figure 4-Flow release restrictions assigned to RZs for various return periods

Not all RZs could realistically be capable of complying with implementation of the assigned restriction due to their extension or site-specific characteristics. Previous condition would open to the possibility of considering fee/credits mechanisms for partial transfer of release restrictions among RZs thus sharing responsibility for storm water control.

6 CONCLUSIONS

Results of the evaluation of the UDMP impact on the hydrology of the Acquicella catchment, in southern Italy, are presented in this paper.

SWMM model was used to compare catchment flow peak releases under scenarios of urban pre- and post-development and to derive a set of flow release restrictions for master plan cluster areas of development. Release restrictions were assessed to comply with hydraulic invariance at the sub-catchment level for different return period of the storm-water event.

Release restrictions were allocated among areas by assuming the penalty due to increased storm-water flows to be assigned to RZs where land use transformations will take place and proportionally to the extent and type of these transformations.

Obtained results showed that release restrictions could be achieved by implementation of source control measures for lower return periods while simulations associated to higher return period events provided higher release restrictions which would open at implementation of concentrated detention based measures within RZs.

Additional research on economic and legal aspects connected to marked-based mechanisms should be conducted in order to validate feasibility of the use of fee/credits mechanisms to transfer burdens among RZs within the same sub-catchment.

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