Assessing the urban catchment hydrologic response under different environmental scenarios

Evaluation de la réponse hydrologique d'un bassin urbanisé par rapport aux différentes conditions environnementales

Palla Anna and Gnecco Ilaria

Dept. of Civil, Chemical and Environmental Engineering, University of Genova
anna.palla@unige.it; ilaria.gnecco@unige.it

RÉSUMÉ

La croissance des surfaces imperméables dans le milieu urbain modifie significativement la réponse pluie-débit à l'échelle du bassin versant. En effet la réduction du sol perméable et de la végétation implique la réduction des pertes hydrologiques (interception, évapotranspiration et infiltration) et aussi l'accroissement des intensités et volumes de ruissellement de surface. Parallèlement au développement urbain, l'impact potentiel du changement climatique est un autre facteur qui influence la vulnérabilité des villes aux inondations. Dans cette étude, l'application de stratégies d'aménagement contribuant à diminuer l'imperméabilisation, appelées par certains auteurs "Low Impact Development (LID) technologies", est analysée afin de compenser l'impact du changement climatique sur l'hydrologie urbaine. Les solutions LID regroupent différentes mesures de gestion durable des eaux de pluie comme par exemple les jardins de pluie, les bandes filtrantes, les toitures végétales et les pavages perméables qui doivent être appliqués à l'échelle du quartier. La réponse pluie-débit d'un quartier résidentiel dans la ville de Gênes (Italie) est examinée par rapport aux différentes conditions de précipitations et niveaux d'urbanisation prévue du territoire. Les résultats du modèle confirment que la mise en œuvre de mesures LID a une incidence positive sur la réduction des eaux de ruissellement en régularisant les effets de la variabilité des précipitations.

ABSTRACT

The growth of impervious surface in urban areas significantly affects the hydrologic response at the catchment scale, indeed the reduction in natural soils and vegetation contribute to reduce the hydrological abstractions (including interception, evapo-transpiration and infiltration processes) and to increase runoff rates and volumes. Additionally to the ongoing urbanization, the potential impact of climate change is another factor affecting the vulnerability of urban areas in terms of flooding occurrence. In this paper, the implementation of Low Impact Development systems (LIDs) is analysed as a source reduction approach to compensate the adverse impact of possible global warming scenarios on urban hydrology. LID solutions include storm water infiltration systems, rain gardens, storm water wetlands, green roofs and permeable pavements to be properly distributed throughout the urban area. The hydrologic response of an urban catchment in the town of Genoa (Italy) is investigated under various environmental scenarios including different precipitation conditions and land use modifications. Modelling results confirm that the installation of LIDs partially compensates the expected increase of rainfall intensities in the design event.

KEYWORDS

Climate change, green roof, LID, permeable pavement, resilience, SWMM

1 INTRODUCTION

In the last decades the increasing urbanisation produces numerous impacts. Focusing on the hydrologic aspects, the reduction of perviousness in urban areas compared to natural land uses causes increasing runoff rates and volumes and limiting evapotranspiration and interception (Jacobson, 2011). It is shown in the literature that a reduction of the impervious area directly connected to the storm drainage system (Effective Impervious Area, EIA) could compensate the adverse impact of the increasing hydrological stress on urban areas.

Low Impact Development (LID) principles and applications represent a possible solution to reduce the EIA fraction on a urban catchment; furthermore LID source control solutions (including green roofs, permeable pavements…) are designed to mimic the pre-development hydrologic conditions thus promoting storage, infiltration and evapotranspiration processes (Palla et al., 2015).

The increasing hydrological stress on urban areas is even more critical if future climate scenarios are considered. In particular it emerges that the Mediterranean region is characterized by a relative low capacity for adaptation due to dense population and over-exploited natural resources including land (Paxian et al. 2015). Referring to the trends of extreme events, results on climate change effects are spatially heterogeneous, further findings are quite controversial on Mediterranean area where high-resolution climate model simulations are required in order to account the complex orographic and land-sea contrasts (Giorgi and Lionello, 2008). Numerous studies reported in the literature documents that Mediterranean regions reveal decreasing in number of wet days and/or total rainfall amounts but increasing in extremes (e.g. Christensen and Christensen 2003; Willems et al., 2011); in particular Kostopoulou and Jones (2005) revealed increasing frequencies of intense rainfall events over Italy.

The ability of the LIDs to absorb and rebound from weather extremes and climate variability and continue to function (resilience) is nowadays investigated at the urban catchment scale in order to include these principles and applications in the climate adaptation plan for municipalities. In this framework, the main objective of the present study is to assess the resilience of urban drainage system to the climate change scenarios when LID control solutions are installed at the catchment scale. The first specific objective is to simulate the hydrologic response of an urban catchment characterized by different land-use scenarios under different climate change scenarios. For this purpose different land use conversion scenarios (i.e. EIA reductions) as well as future precipitation scenarios are considered and the hydrologic response of an urban catchment including LID solutions is undertaken using the EPA SWMM. The second specific objective is to to assess the impact of green roofs and permeable pavements on the hydrologic response under future precipitation scenarios; for this purpose the hydrologic resilience rate is measured through three specific indexes with respect to the hydrograph peak, volume and time response.

2 METHODOLOGY

2.1 Site description

The urban catchment of Colle Ometti, in the town of Genoa (Italy) is selected as a test site for the hydrologic modelling of land use conversion scenarios. This 5.5 ha catchment was urbanised in the eighties with 500 houses built on a previously undeveloped hill slope. The management of storm water is addressed according to the traditional approach; in particular the separate sewer system consists of a main collector and eight lateral sewers and no LID source control solutions (green roofs and permeable pavements) are installed in the catchment. Table 1 illustrates the land use characteristics of the catchment and the percentage of total impervious and pervious areas. The analysis of land use data reveals that 60% of the Colle Ometti catchment is covered with impervious surfaces and that rooftops account for 31% of the total areas.

Table 1 Land use characteristics of the urban catchment.

Land use	***Area***	
	[ha]	**[%]**
Rooftop	1.41	31
Road and Parking Lot	1.28	28
Other impervious	0.06	1
Total Impervious	*2.75*	*60*
Green Area	1.28	28
Farmland	0.53	12
Total Pervious	*1.81*	*40*
Total Areas	*4.56*	*100*

2.2 Environmental Scenarios

2.2.1 Land use conversion scenarios

Green roofs and permeable pavements are the LID source control solutions selected for the implementation within the urban catchment. Table 2 illustrates the land use conversion scenario and the corresponding EIA reduction percentage. In particular, the proposed scenarios are designed combining the following criteria: four percentages of rooftops conversion (namely 0%, 20%, 50% and 100%) and a single ratio of road and parking lot (namely 16%) corresponding to the whole public parking area. As for land use characteristics, the current configuration which corresponds to the ‘‘do nothing’’ scenario is used to evaluate the hydrologic response in the “control” scenario.

Table 2 Land use conversion scenarios and EIA reductions.

LID source control solution	***Conversion Scenario***			
	I	**II**	**III**	**IV**
Green roof [% of Rooftops]	0	20	50	100
Permeable Pavement [% of Road and Parking Lot]	16	16	16	16
EIA reduction [% of Catchment Area]	5	11	21	36

2.2.2 Climate change scenarios

In order to investigate the resilience of an urban catchment to climate change effects, the hydrologic response is evaluated by varying the rainfall event characteristics. The current rainfall conditions are derived by analysing the rain data collected at the rain gauge station of Genoa Villa Cambiaso (1990–2013) and 2-year return period synthetic hyetograph is used as input. The synthetic hyetograph is calculated using the Chicago methods by assuming 30-minutes rainfall duration and the time-to-peak ratio of 0.5. The LID control solutions are designed in order to retain the high-frequency rainfall events and to detain medium-to-low-frequency rainfall events; further the design storm for urban drainage system should be 10-years return period. Therefore the 2-year return period hyetograph is selected to estimate the LID performance being significant rainfall event conditions for drainage systems.

In the present study the climate change conditions are evaluated by using the climate change factor that is defined as the ratio between the rainfall intensity for a given duration and return period for a future climate scenario and the corresponding rainfall intensity in the current conditions (Arnbjerg-Nielsen, 2012). Although the climate change factor is affected by both the local/regional climate conditions and the rainfall characteristics (return period and duration), the uncertainties associate to the climate change simulation scenarios and their application to urban hydrology is an open-debate issue. In light of such considerations and results reported in the literature (Larsen et al., 2009; Rodriguez et al., 2014) it is reasonable to suppose the 20%-increase of the rainfall intensity for the case study of concern. In particular, the climate change factor (CCF) is assumed ranging between 1.05 and 1.20 in step of 0.05; thus the rainfall intensity corresponding to different climate change scenarios is calculated by multiplying the current rainfall intensity by the CCF.

2.3 EPA SWMM model

The EPA Storm Water Management Model (SWMM) (Rossman, 2010) is selected to simulate the hydrologic response of the urban catchment. Recently LID control modules have been implemented in SWMM (v. 5.1.007) in order to simulate the hydrologic performance of source control solutions such as rain gardens, green roofs, infiltration trenches and permeable pavements. LID systems are represented by a combination of vertical layers whose properties (such as thickness, void volume, hydraulic conductivity, underdrain characteristics, etc.) are defined on a per-unit-area basis; LIDs can be assigned within selected subcatchments by defining the corresponding areal coverage.

The study area is simplified in 286 subcatchments, 102 junctions and 101 conduits; this high-resolution discretization results in subcatchment areas characterized by single land use type and homogenous properties. Consequently, the LIDs are applied to selected subcatchments and occupy the full subcatchment area (i.e. roof surface is converted into green roof). In the present study, the Soil Conservation Service Curve Number Method is used to estimate infiltration losses and runoff is calculated using the Manning's equation. As for flow routing computation, the dynamic wave theory is used. Detail description of the model calibration is available elsewhere (Palla and Gnecco, 2015).

3 RESULTS

Model results consist of the outflow hydrographs for the reference and selected conversion scenarios. The reference scenario corresponding to the "do nothing" scenario is simulated under the current rainfall condition (namely "control hydrograph") while the four conversion scenarios are simulated under different climate change scenarios. In detail, the current rainfall conditions is assigned equal to the 2-year return period event and the climate change scenarios are selected based on climate change factors of 1.05, 1.10, 1.15 and 1.20.

The hydrologic resilience of the land use conversion scenarios is assessed through three indexes: the peak, volume and time response resilience rates. For each conversion scenario, the peak resilience rate is calculated as the relative percentage difference between the outflow peaks of the control and climate change scenarios; the volume and the time response rate are similarly evaluated. In particular the time response is calculated based on the hydrograph centroids of the control and the climate change scenarios.

Figure 1 shows the hyetographs and the corresponding simulated hydrographs for the four conversion scenarios at assigned climate change conditions; in each graph the control hydrograph (indicated as blue line) is reported. Looking at the hydrographs reported in Figure 1, the larger is the EIA reduction, the lower is the peak flow rate; in particular for the less severe climate change condition corresponding to CCF of 1.05 even the minimum land use conversion scenario (EIA Reduction = 5%) is almost resilient for the peak flow rate while for the most severe climate change condition (CCF = 1.2) an EIA reduction of 21% is required to obtain an outflow peak rate lower than the control one. The timing of the hydrologic response is consistent between the hydrographs of the same conversion scenario irrespective of the climate change conditions and in particular the lag time and the time-to-peak are constant.

In Figure 2, the hydrologic resilience indexes referred to the runoff volume, peak flow rate and response time are plotted versus the EIA reduction percentages with respect to the four climate change scenarios (CCF=1.05; 1.10; 1.15; 1.20) for the 2-year return period event. Results point out that the hydrologic resilience indexes are linear dependent on the EIA reduction. The peak resilience index reveals the best performance as confirmed by the steeper regression lines. The volume resilience index shows the lowest values thus pointing out the dependence with the retention capability of the LID (such as the void ratio and depth) that is limited being the climate change scenarios characterized by increasing rainfall volume. The response time resilience index shows a peculiar trend that is the system is always resilient and the resilience rate is the same for all the climate change conditions thus confirming the capability of LIDs in delaying the catchment response.

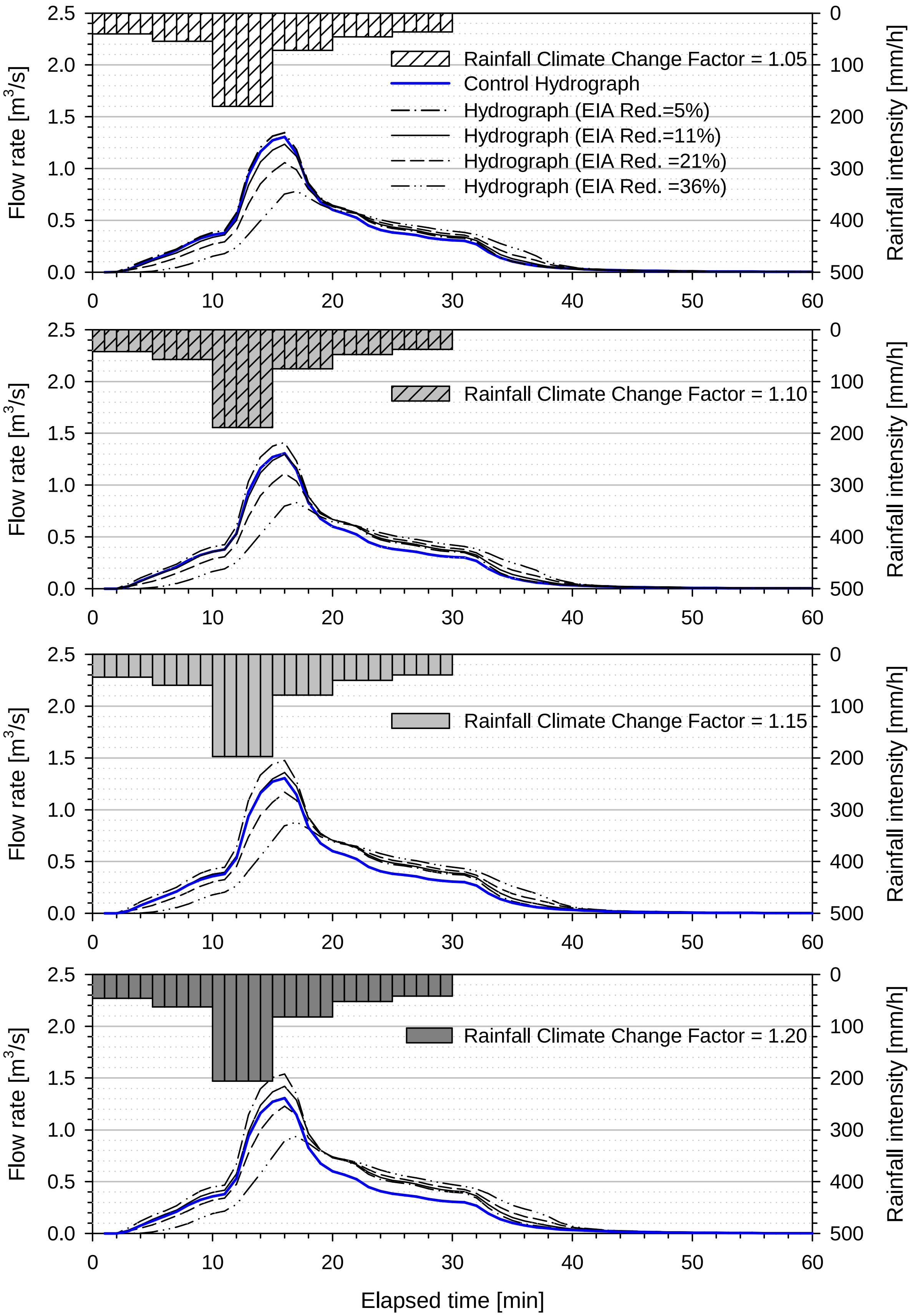

Figure 1 The hyetographs, the corresponding hydrographs simulated for the different EIA reduction scenarios at assigned climate change scenario (CCF=1.05; 1.10; 1.15; 1.20) for the 2-years return period event. The control scenario indicates the “do nothing” scenario at current rainfall condition.

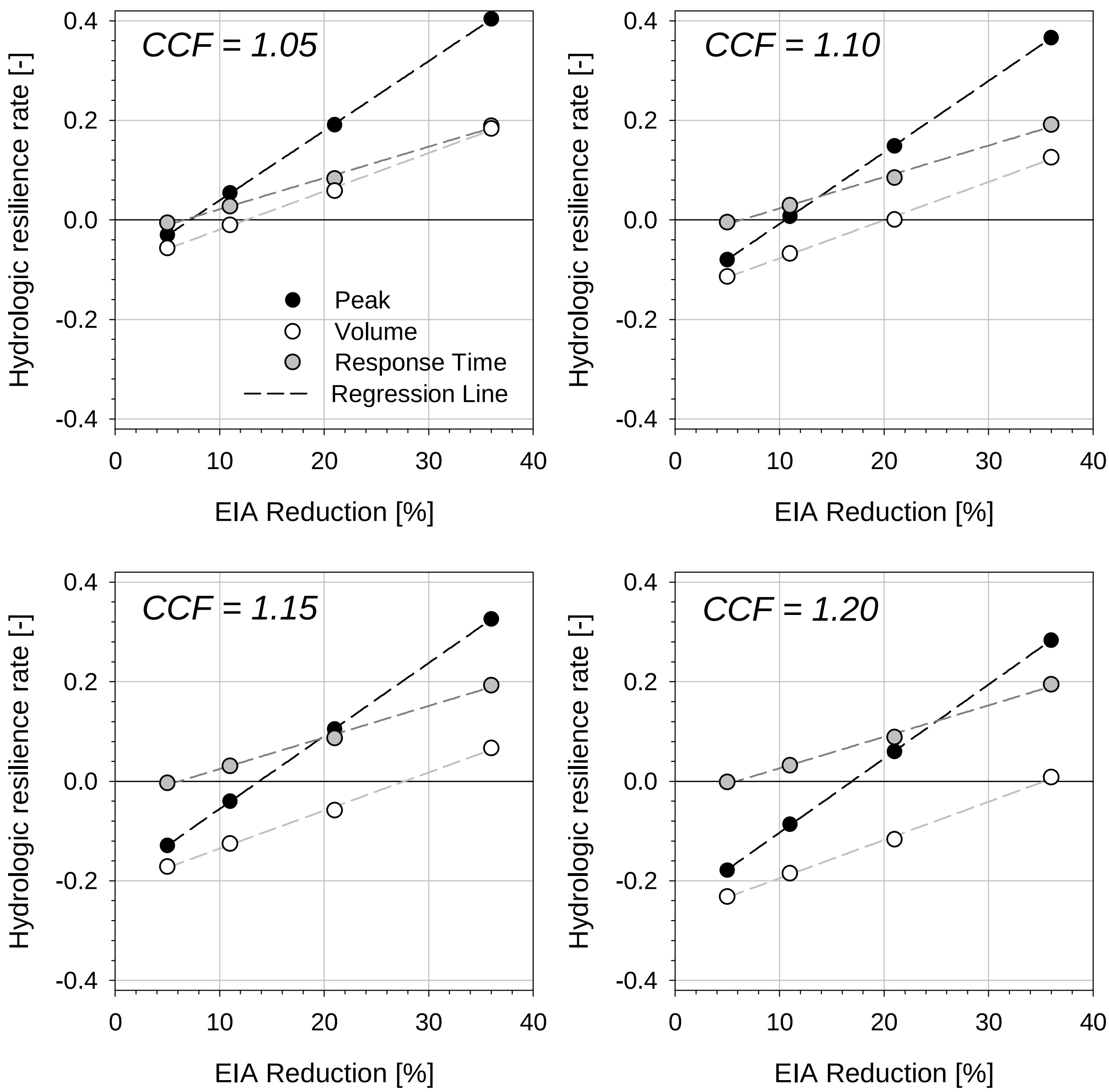

Figure 2 Hydrologic resilience rate vs the EIA reduction at assigned climate change scenario (CCF=1.05; 1.10; 1.15; 1.20) for the 2-years return period event.

In Figure 3, the hydrologic resilience indexes referred to the runoff volume, peak flow rate and response time are plotted versus the climate change factor with respect to the four conversion scenarios (EIA Reduction=5%; 11%; 21%; 36%) for the 2-year return period event. Results point out that the hydrologic resilience indexes decrease linearly with the CCF. The exception occurs with the time response resilience index that is fairly constant thus confirming that the response time of the catchment response does not vary with the climate change conditions (being it referred to an extreme event). The 5%-conversion scenario is not resilient for both the peak and volume for all the climate change scenarios, while the 36%-conversion scenario is resilient for all the variables. The 11%-conversion scenario allows to compensate the increase in the peak flow due to a CCF=1.1 while in order to compensate the increase in the volume is needed the 21%-conversion scenario.

4 CONCLUSIONS

The hydrologic response of a small urban catchment has been simulated under different environmental scenarios implementing various land use conversion scenarios and hypothesizing future precipitation conditions. Four land use conversion scenarios have been designed including installation of green roofs and permeable pavements and four future precipitation scenarios have been defined assuming the climate change factor between 1.05 and 1.20 in step of 0.05. The EPA SWMM including the LID control modules has been implemented at high spatial resolution in order to assess the resilience of the selected LIDs to future precipitation scenarios.

Modelling results confirm the role of LID solutions in restoring the critical components of the natural flow regime at the urban catchment scale; in particular the catchment resilience to the climate change is estimated through three specific indexes with respect to the hydrograph peak, volume and time response.

The hydrologic resilience indexes are linear dependent on the EIA reduction and the peak resilience index reveals the best performance. As expected, the higher is the EIA reduction the higher are the resilience rates; in particular the 5%-conversion scenario is not resilient for both the peak and volume for all the climate change scenarios, while the 36%-conversion scenario is resilient for all the variables.

The proposed EIA reduction strategy suggests that LIDs can play an important role in climate adaptation planning for municipalities; through the use of LID practices, resiliency can be planned into a urban catchment.

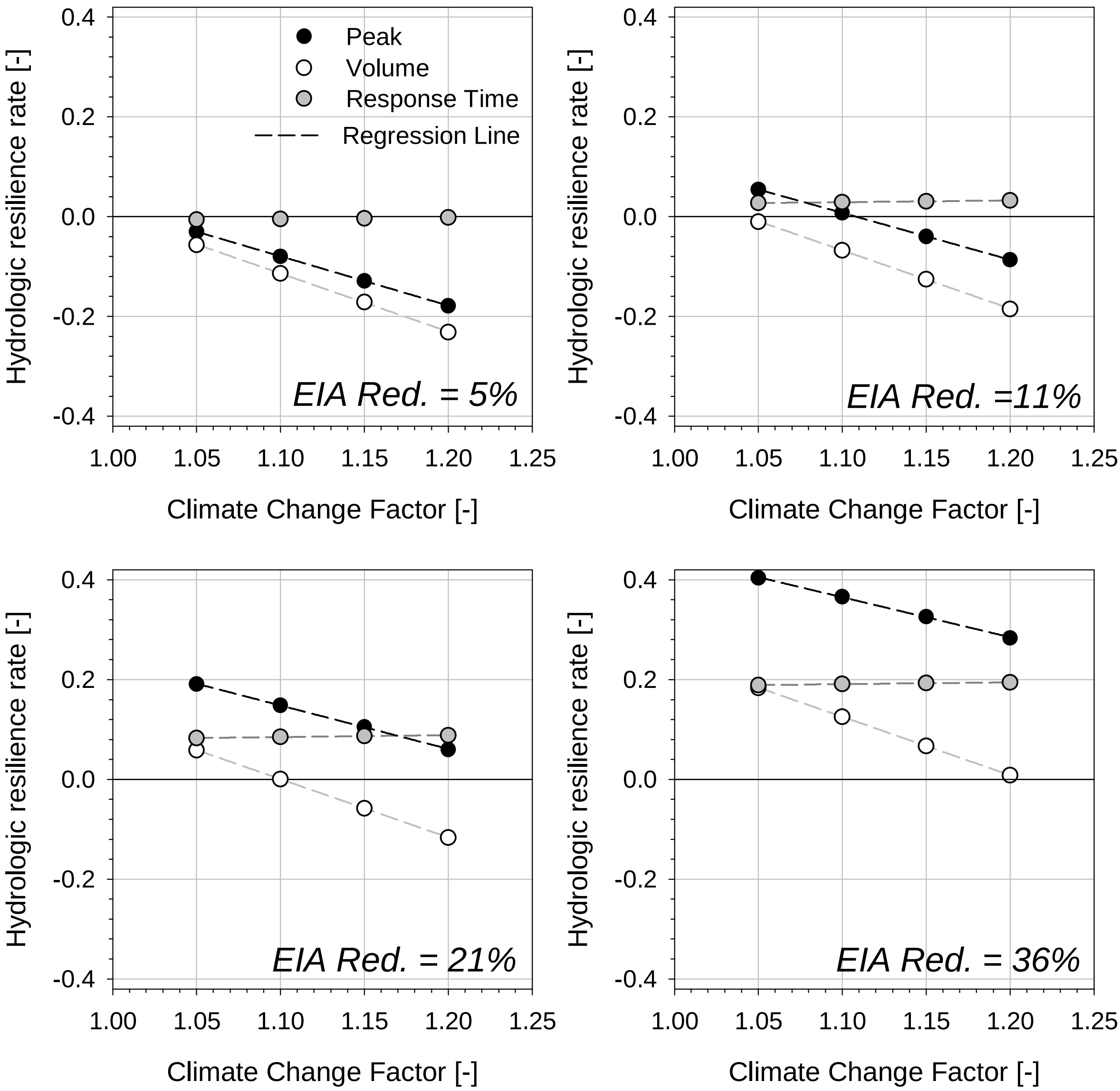

Figure 3 Hydrologic resilience rate vs the Climate Change Factor at assigned land use conversion scenario (EIA Reduction = 5%; 11%; 21%; 36%) for the 2-years return period event.

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