Assessing the impact of rainwater harvesting on the hydrological regime of small semi-urban watersheds

Jérémie Sage, Emmanuel Berthier, Clément Dutremble, Delphine Porcheron

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Impacts de le récupération des eaux pluviales sur le régime hydrologique de petits bassins versants partiellement urbanisés

Sage J.[1*], Berthier E.[1], Dutremble C.[1], Porcheron D.[1],

[1]Cerema, Equipe-projet TEAM, 12 rue Teisserenc de Bort, 78197 Trappes (*jeremie.sage@cerema.fr) ;

RÉSUMÉ

La récupération des eaux de pluie suscite aujourd'hui un intérêt croissant du fait des incertitudes sur la disponibilité future des ressources en eau. Celle-ci est par ailleurs fréquemment envisagée comme un moyen de limiter à la source les volumes de ruissellement générés niveau des surfaces revêtues, participant ainsi à la gestion des eaux pluviales urbaines. La perspective d'une mise en œuvre de politiques incitatives de récupération des eaux pluviales impose cependant de s'interroger sur l'incidence de cette pratique sur le régime hydrologique de certains bassins versants. Dans les secteurs urbanisés, pour lesquels le potentiel de développement de la récupération des eaux pluviales est important, l'interception d'une fraction significative du ruissellement pour satisfaire divers usages pourrait en effet conduire à un déséquilibre hydrologique se traduisant par une aggravation des étiages. Une méthode associant modélisation hydrologique et exploitation de données géographiques est ici introduite pour construire différents scénarios de récupération des eaux pluviales et évaluer leur incidence de sur le régime hydrologique deux bassins-versants semi-urbains. L'analyse suggère ici que cette pratique n'est à elle seule pas suffisante pour satisfaire les objectifs usuels de gestion des eaux pluviales mais indique que sa systématisation sur des têtes de bassins versant présentant de faibles débits pourrait en revanche donner lieu à une aggravation des étiages.

ABSTRACT

Rainwater harvesting is a relevant and sustainable solution to reduce the pressure on conventional water resources. Rainwater harvesting techniques can as well provide stormwater management benefits through the reduction of runoff volumes. The impact of a wide implementation of these practices on the hydrological regimes of already disturbed catchments however remains unclear. The capture of significant fraction of runoff volume in urbanized areas to satisfy various uses, could in particular result in an over-extraction of water, exacerbating low streamflow issues. In this study, a method associating geodata processing and allotment-scale hydrological modeling is introduced to investigate the impact of rainwater harvesting on the hydrology of two semi-urban catchments, addressing both stormwater management benefits and low-flow effects. Results indicate that rainwater harvesting alone is unlikely to meet usual runoff-control objectives, but as well suggest that a systematic implementation of these practices on upstream catchments that already face low water flow issues might be detrimental to stream health.

KEY WORDS

Low-flow; Reuse; Runoff-reduction; Stormwater; Stream health

1 CONTEXT AND OBJECTIVES

Rainwater harvesting has become a relatively common technique to reduce potable water consumption and is likely to develop in the next decades due to the uncertainty regarding the availability of water resources. This practice usually relies on relatively basic systems that convey runoff originating from impervious surfaces (in most cases roof surfaces) to simple storage units such as rainwater tanks or barrels. Collected volumes can then supplement traditional domestic water supply for outdoor or indoor uses that do not require drinkable water quality standards. Because rainwater harvesting may provide non-negligible volume reduction at the local scale, it also increasingly seen as a solution that complements more conventional stormwater source-control systems (swales, rain gardens…) (Walsh et al., 2014; Steffen et al., 2013).

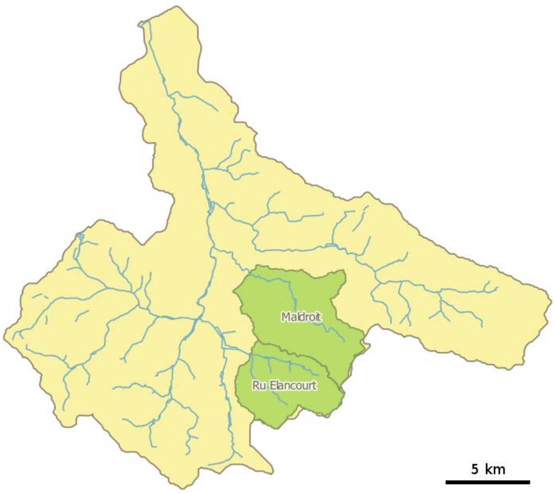
The hydrological functioning of rainwater harvesting (RWH) systems however significantly differs from other stormwater management solutions (Gerolin et al., 2010). Volume reduction primarily depends on initial storage conditions governed by irregular rainwater inflows and drawdowns; the effect of RWH system therefore tends to be highly variable. The impact of these techniques on the local water cycle is also likely to differ significantly from other volume-reduction techniques; whereas the latter usually rely on infiltration (resulting in the release of a fraction of collected volumes as baseflow), RWH practices may simply divert harvested volume out of the catchment (Fletcher et al., 2007). This alteration of the water cycle can potentially affect surface waters, especially during low-flow periods. The growing interest in RWH and its potential development to face the effects of future climate or consumption changes on water resources therefore requires to investigate its impact on the hydrological regime of vulnerable catchments.

In this study, the consequences of RWH are illustrated for two small semi-urban watersheds experiencing recurring low-flow and flooding issues. A simple coupled GIS and hydrological modeling approach is introduced to compare different RWH scenarios in terms of uses and storage options.

2 METHODS

2.1 Study area

Study area consists of two semi-urban sub-catchments of the Mauldre river located in western Paris region (Yvelines department), comprising both relatively dense urban centers and peri-urban areas. The main characteristics of the two catchments are presented hereafter:



Characteristics	Ru d'Élancourt	Maldroit
Total area	22 km²	32 km²
Urban cover	54%	47%
Annual discharge	490 mm	125 mm
QMNA5[1]	129 l/s	59 l/s
Total discharge for QMNA5	15.6 mm	4.9 mm

[1]Mean monthly low-flow value for the 5 year return period (usual indicator of low-low periods in France)

Fig. 1 - Study area and catchment characteristics

2.2 Hydrological modeling

The modeling of RWH system is conducted at the allotment scale for each parcel of two catchments (up to 12 000 computation units, depending of RWH scenario). A simple conceptual model (similar to the one presented in Mitchell et al, 2008) is here adopted to simulate runoff production on roof surfaces, storage and drawdown for indoor or outdoor uses. Hydrological processes such as runoff generation from remaining urban surfaces or agricultural areas are not represented here.

Simulations are conducted at an hourly time step using 15-year long meteorological records. Monthly volume reductions computed with the hydrological model are then compared to flow-rate values measured at the outlet of the two catchment so as to evaluate the potential impact of RWH on low-flows. Stormwater management benefits are additionally discussed on the basis of annual volume reductions and total storage volumes associated with each RWH scenario.

2.3 Construction of rainwater harvesting scenarios

A RWH scenario may be described as the combination of a storage (e.g. sizing of the RWH system) and a water demand scenarios. While different demand scenarios were considered in this study, the article focuses on a single "maximum scenario" for which RWH is implemented (i) on every individual housing lots to cover both indoor and outdoor uses and (ii) on collective housing and public buildings for outdoor uses only (parcel types are identified from public databases).

The demand associated with outdoor uses is here limited to garden and landscape irrigation. An outdoor demand time-series is computed for each parcel from geographical data (to derive irrigation area) and potential evapotranspiration measurements using the method described by Nouri et al. (2013). Indoor demand is deducted from water consumption statistics and an estimation of the number of inhabitants on each individual housing lot. The sizing of RWH systems is adapted for each demand scenario using the method described in de Gouvello et al. (2010). An optimization is therefore performed for each parcel so as to meet water demand while keeping reasonable storage volumes (here limited to 2 m^3 for 100 m^2 of roof surface).

Water demand estimates and corresponding storage volumes are strongly dependent on the assumptions adopted to compute indoor and outdoor uses (geographic data processing, hypotheses regarding domestic water consumption, parameterization of irrigation needs…). Uncertainties associated with the definition of each RWH scenario are thus accounted for by considering lower and upper bounds for the water demand. Here, the combination of outdoor and indoor demand ("maximum scenario") D_{TOT} is found to represent between 120 and 230 mm/year at the catchment scale.

3 RESULTS

The table below shows the total storage volume V_{TOT} (m^3), the volume reduction efficiency ε (mm) and the proportion of the annual water demand covered by RWH T_R (%) for selected scenario (indoor and outdoor uses for individual housing lots and outdoor uses for public buildings and collective housing).

Table 1. Simulation results for the "maximum" RWH scenario (considering uncertainties regarding water demand)

Indicator	Ru d'Elancourt	Maldroit
V_{TOT}	17 800 to 18 000 m^3	17 900 to 18 100 m^3
T_R	7 to 13 %	9 to 16 %
ε	13 to 16 mm	9 to 11 mm

Table 1 primarily indicates that the total storage volume V_{TOT} computed for each catchment with the automatic sizing procedure remains mostly constant, despite large uncertainties regarding water demand D_{TOT}. Here, the increase between lower and upper estimates of D_{TOT} (from 120 to 230 mm/year) can believably not be satisfied through RWH unless considering unrealistic storage volumes (discarded by the automatic sizing procedure). T_R hence exhibits large variations that are directly related to D_{TOT}. T_R values nevertheless remain relatively low suggesting that the total production (e.g. roof) area is not sufficient to meet irrigation requirements that represent more than 90% of D_{TOT} (additional test clearly demonstrate that indoor demand is much easier to satisfy as it does not exhibit the same variations as watering needs that are maximized during dry periods).

V_{TOT} represents less than 1 mm at the catchment scale and is therefore very unlikely affect highest stream flows, although it remains significant at the roof scale (approximately 19 mm) and may hence provide on-site volume attenuation for medium to large rain events. Similarly, the annual volume reduction ε does not exceed 16 mm at the catchment scale but represents more than 50% of the annual roof runoff. Despite a limited effect at the catchment scale (where roofs represent less than 5% of the total area), RWH could hence clearly complement other stormwater management systems at the allotment scale.

Monthly volume reduction ε_{mth} associated with RWH are presented in figure 2 and compared to low-flow values measured at the outlet of the two catchments:

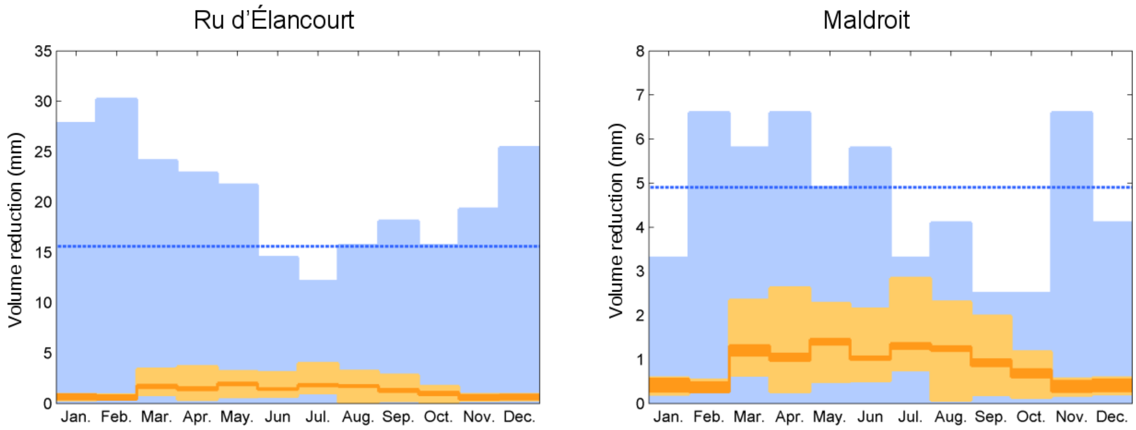


Fig. 2 – Monthly volume reductions on the two catchments. Dark orange: average volume reduction; Light orange: minimum and maximum volume reduction; Light blue: minimum monthly flow-rates measured at the outlet of the catchment ; Blue dotted-line: low flow indicator QMNA5 (cf. Table 1)

The impact of RWH tends to be more important for the Maldroit catchment that exhibits significantly lower stream flows than the other one (cf. Table 1). For this catchment, ε_{mth} may represent a large fraction of minimum stream-flow values (although maximum values shown in light orange are clearly not associated with dry low-flow periods). Average ε_{mth} values computed for July and August hence reach between 10 and 15% of average stream-flow volumes whereas minimum ε_{mth} values for instance exceed 20% of the minimum volume observed in July.

Results hence suggest that, for the Maldroit catchment, low-flow issues could potentially be exacerbated by RWH practices. It is however important to underline that the scenario tested here is based on the assumption of a systematic implementation of RWH at the catchment scale and should thus not be considered at totally realistic.

4 CONCLUSION AND PERSPECTIVES

A relatively simple method was developed to generate and simulate various RWH scenarios from hydrological and geographical data available from public geographical databases.

In this application, RWH was not found to provide significant benefits at the catchment scale ; volume reduction achieved for idealistic development scenarios remains very limited unless focusing roof surfaces, for which RWH should nevertheless be completed by more conventional runoff-control practices. Results also indicate that RWH could under specific conditions (upstream catchments with low stream flows) result in an excessive abstraction of runoff volumes during low-flow periods.

While the method adopted here offers perspective for a wider scale assessment of the effect of RWH, its integration in a more comprehensive modeling framework, incorporating other hydrological processes such as rainfall-runoff transformation, would believably be beneficial for a more detailed examination of the hydrological impacts of RWH practices.

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