Effects of rainwater harvesting on centralized urban water supply systems
C. Grandet, P. J. Binning, P. S. Mikkelsen and F. Blanchet

Abstract
The potential effect of widespread rainwater harvesting practices on mains water demand and quality management are investigated for three different types of urban areas characterized by different roof area to water demand ratios. Two rainfall patterns are considered with similar average annual depths but very different temporal distributions. Supply reliability and the extent of reliance on the public distribution system are identified as suitable performance indicators for mains water infrastructure. A uniform temporal distribution of rainfall in an oceanic climate like that of Dinard, Northern France, yielded supply reliabilities close to 100% for reasonable tank sizes (0.065 m$^3$/m$^2$ of roof area in Dinard compared with 0.262 m$^3$/m$^2$ in Nice with a RWSO of 30% for a detached house). However, the collection and use of rainfall results in a permanent decrease in mains water demand leading to an increase in water age in the distribution network. Investigations carried on a real network showed that water age is greatly affected when rainwater supplies more than 30% of the overall water demand. In urban water utilities planning, rainwater supply systems may however be profitable for the community if they enable the deferment of requirements for new mains water infrastructure.

Key words | economic assessment, rainwater harvesting, urban water cycle management and planning, water balance model

Introduction
In developed countries, drinking water supply is generally managed by means of centralized utilities. Rainwater harvesting is commonly considered to have multiple benefits because it reduces drinking water uptake from public distribution networks and provides some onsite retention storage (Mikkelsen et al. 1999; Coombes & Kuczera 2003; Villareal & Dixon 2004). This article aims to assess the impact of widespread implementation of rainwater utilization in urban areas on existing water supply infrastructure. The behavior of rainwater collection systems is investigated in order to determine whether they can reduce the reliance on centralized water supply systems. Increased rainwater harvesting will decrease demand from centralized drinking water supplies and therefore increase water residence times in distribution systems. The implications in terms of water supply demand and quality management are subsequently discussed. Finally, a brief qualitative economic analysis of rainwater harvesting is presented.

Methodology
Urban water system response in terms of water supply is simulated for three categories of urban areas using a simple water balance model. The larger scale response of the water supply network is simulated using EPANET on a real case study.
Water balance model

Rainwater supply system

A water balance model is constructed for each allotment and includes the contributing area (roof) and a storage volume (tank) with an overflow structure connected to the stormwater drainage network. The volume of rainwater drawn from the tank during each time step (24 hours) is related to the number of occupants. Once emptied, the rainwater tank is filled by means of mains supplied drinking water. The amount of roof runoff that flows into rainwater tanks is assumed to be 90% of rainfall, to account for initial losses, possible overflow from the gutter and other losses due to evaporation and wind direction (Ragab et al. 2003).

The fraction of the overall demand to be supplied by rainwater is referred to as the Rainwater Supply Objective (RWSO). The size of the rainwater storage is expressed per square-metre of contributing roof area, and is referred to as the Specific Tank Volume (STV).

Rainfall data

In order to assess the effects of rainwater supply systems under various climates, the water balance model was run for two distinct rainfall time series. The rainfall data was from two French cities, Dinard and Nice, characterized by respectively oceanic and mediterranean climates. The average annual precipitated depths are similar for Dinard and Nice over the selected periods, being 775 mm per year (01/01/2004–31/12/2006) and 759 mm per year (01/01/2000–31/12/2003) respectively. However, rainfall distributions are quite different. For example, the mean annual number of rainy days is 194 in Dinard while there are only 50 in Nice over the considered periods (Figure 1).

Type of urban area

Rainwater supply systems can be installed in various types of urban buildings, and here three general categories are considered (Table 1). Each category is assigned a roof area per occupant ratio and a range of possible RWSO is considered. The values shown in the table are based on three arbitrarily selected urban areas in Bussy-Saint-Georges and Villepinte (France). These areas were selected because they each represent a common type of urban development and have a homogeneous building typology.

Roof surface areas are determined from satellite pictures. The number of occupants of collective housing buildings and detached houses are determined for typical French conditions (INSEE 1982–1999) where there are on average 4 occupants or person equivalents (PE) per individual detached house; 2.5 PE per apartment in collective housing buildings; and daily water demand is 150 liters per day per PE throughout the year.

Water demand from commercial and office buildings are estimated using data from Satin & Selmi (1999), and then expressed in terms of PE in order to be consistent with residential districts. The rainwater supply objective (RWSO) is determined by potential rainwater use (Montginoul 2002). For example, in commercial and office buildings, toilet flushing and cleaning account for most water demand, which suggests that a RWSO between 20 and 70% is realistic.
The effects of widespread implementation of rainwater supply systems on a large scale are assessed on the network of a French municipality (Figure 2) with the EPANET modeling tool.

Description of the network

The northern part of the municipality, where the network is dense, is about 800 Ha. The considered network comprises 1,770 nodes supplied by three waterworks. The waterworks situated in the north-western part is connected to a reservoir, whereas the others supply the network through direct pumping. The selected area is hydraulically independent from neighbouring distribution systems. The public distribution network in the considered area is designed to meet fire flow requirements. In residential areas, the minimum required flow from a fire hydrant is 60 m³/hr for two hours with a dynamic pressure head of at least 10 m. Moreover, the maximum distance by the road between two fire hydrants is 200 m (Circulaire interministérielle no 465 1951).

Simulation parameters

The EPANET model file of this system was provided by Veolia Eau (2004). Demand and pressure on each node of the network were determined by Veolia Eau (2004) from a monitoring program. A traditional domestic demand pattern was used for all nodes despite some small commercial and industrial water users. Decreases of mains water demand due to rainwater use is implemented in the model by multiplying the diurnal water demand pattern by 0.8 for 20% rainwater use, 0.7 for 30% and 0.6 for 40%. Simulations are run over 192 hours (8 days). Such a long simulation time is needed to obtain stable simulation results. It is assumed that there is enough rainwater storage to meet rainwater demand for the whole simulation period.

RESULTS AND DISCUSSION

The effect of widespread implementation of rainwater harvesting systems on the public drinking water supply system is investigated in terms of water demand management and water quality management.

Supply reliability of rainwater harvesting systems

The allotment scale water balance model is used to evaluate the reliability of rainwater supply systems. In developed countries, where potable water is constantly available from the tap, supply reliability is a key indicator to assess alternative water supply sources. A behavioral analysis of rainwater supply systems was conducted by Mitchell et al. (2005) who introduced the concept of supply reliability over a given period, which is defined to be the percentage of rainwater demand that is actually supplied.
The ability of rainwater harvesting systems to reduce reliance on centralized drinking water supply systems is investigated. The necessary STV to achieve 95% volumetric reliability—considered as acceptable reliability—in various conditions are presented in Table 2 (the marginal efforts to get closer to 100% reliability are very heavy).

The necessary STV are strongly related to the roof area per occupant ratio. This parameter is quite favorable to rainwater supply systems in commercial and office buildings. The reliability results show that rainwater supply systems are most efficient in business parks as 95% reliability can be achieved in Dinard for a STV below 0.1 m³/m² with rainwater demands up to 60%. A much higher STV is required in Nice, but in the context of business parks, space constraints are less significant than in collective housing or detached house districts. The impacts of climate on the performance of rainwater harvesting systems is also well illustrated here: a 95% volumetric-reliable rainwater supply system replacing 20% of mains water demand in a detached house with 100 m² of roof area would require tank volumes of 2.1 m³ in Dinard compared with 13.3 m³ in Nice.

When assessing the benefits of rainwater harvesting, Coombes & Kuczera (2003) argue that annual savings related to widespread implementation can defer the requirement for new dams for water supply in Australia.

However, an annual time scale is not suitable for the assessment of the effects on mains water production units and distribution networks, which are designed to meet daily or even hourly peak demands. Our analysis of supply reliability shows that rainwater harvesting systems are not likely to be reliable water supply sources when considered in the context of a whole public water supply network. Centralized production and distribution infrastructures must be designed to meet peak water demand, including the full back up of rainwater harvesting systems in case of extended dry periods. Furthermore, network pipe design is generally determined by fire flow requirements (and not peak domestic demand). Adapting network pipes design to reduced water demand would therefore imply planning a fire fighting strategy that does not rely on the dynamic pressure and flow provided by the public distribution network.

**Impacts on mains water demand management**

The water balance model is used to investigate mains water demand and rainwater usage variations as a function of a given time series of rainfall.

Rainwater harvesting systems were previously characterized as non-permanent water supply sources covering up to 70% of water demand. The source of water supplies for an allotment can be modified over one time step (24 hours) when rainwater tanks run dry or when they are replenished after a dry period. These phenomena generate sudden variations of mains water demand and are assessed below.

In practice, the daily water demand of a given urban area is not similar from one day to the next. In order to evaluate the significance of daily mains water demand variations induced by rainwater use, a set of daily mains water production data reported from a municipal network in France is used as reference (Veolia Eau 2004). This data set shows that over the considered period (one full year), daily demand variations:

- remain below 7% for 75% of the time,
- exceed 15% only 5% of the time,
- exceed 25% for only 3 days, and are probably related to maintenance interventions or to failure of some parts of the system.

### Table 2

<table>
<thead>
<tr>
<th>RWSO</th>
<th>Location</th>
<th>Collective housing buildings</th>
<th>Detached houses</th>
<th>Commercial and office buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>Dinard</td>
<td>NA</td>
<td>0.021</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Nice</td>
<td>NA</td>
<td>0.133</td>
<td>0.039</td>
</tr>
<tr>
<td>30%</td>
<td>Dinard</td>
<td>NA</td>
<td>0.065</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>Nice</td>
<td>NA</td>
<td>0.262</td>
<td>0.076</td>
</tr>
<tr>
<td>40%</td>
<td>Dinard</td>
<td>NA</td>
<td>NA</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>Nice</td>
<td>NA</td>
<td>NA</td>
<td>0.133</td>
</tr>
<tr>
<td>50%</td>
<td>Dinard</td>
<td>–</td>
<td>–</td>
<td>0.037</td>
</tr>
<tr>
<td></td>
<td>Nice</td>
<td>–</td>
<td>–</td>
<td>0.195</td>
</tr>
<tr>
<td>60%</td>
<td>Dinard</td>
<td>–</td>
<td>–</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>Nice</td>
<td>–</td>
<td>–</td>
<td>0.261</td>
</tr>
<tr>
<td>70%</td>
<td>Dinard</td>
<td>–</td>
<td>–</td>
<td>0.133</td>
</tr>
<tr>
<td></td>
<td>Nice</td>
<td>–</td>
<td>–</td>
<td>NA</td>
</tr>
</tbody>
</table>
Simulations run with the water balance model reveal that the amplitude of daily variations in mains water demand induced by rainwater tanks emptying/filling cycles is quite significant compared to the reference scenario (no rainwater supply). Furthermore, the frequency of significant variations increases as the buffer capacity of the rainwater tank decreases, i.e. for low STV and high occupant per contributing area ratios. Figure 3 illustrates these findings for two configurations under an oceanic climate (rain series from Dinard).

It should be noted that the water balance model only accounts for mains water demand variations due to rainwater use, and that the network model assumes that all rainwater supply systems are perfectly synchronized (they fill in and run dry at the same instant). One consequence is that significant demand variations corresponding to the moment when rainwater tanks run dry are accentuated. In reality, all tanks would not be designed for the same STV and people would not draw water from their tanks at the exact same rate and same moment, so all tanks would not run dry at the same instant. A sudden decrease of mains water demand is, however, quite realistic. Indeed, if most rainwater tanks of a given area have run dry after an extended dry period, they are likely to replenish simultaneously when a rain event starts, causing sudden decrease of mains water demand.

With widespread implementation of rainwater supply systems, the daily mains water demand is likely to become difficult to predict. Sudden reduction of mains water demand is likely to generate overproduction from waterworks. Overproduced water must be stored in reservoirs, which tends to increase water age, and even spilled if reservoirs capacity is exceeded.

Impacts on main water quality management (water age)

Reduction of mains water demand also influences flows of potable water in the distribution network, and hereby the amount of time that water remains in the distribution network, referred to as water age.

Water age is an indicator of bacterial contamination risk. Indeed, a major cause of water quality failure in distribution networks is bacterial growth. This phenomenon is prevented at the waterworks by injecting a disinfection agent (generally chlorine in France) that is transported in the supplied water and reacts throughout the network (Margolin 1997). However, chlorine is degraded as it reacts with organic compounds. Chlorine decay has been thoroughly investigated (Clark et al. 1993; Ozdemir & Ucak 2002) and although the evolution of chlorine concentration in the distribution network depends on parameters related to the condition and size of pipes, a determining factor is water age. The influence of rainwater use on water quality in the distribution network is limited to the investigation of the effects on water age, which are likely to be quite reproducible to any network, whereas the influence of pipe size and condition can vary a lot from one case to another.

Determination of water age in large scale systems requires modeling because water age is space and time dependant, and is related to all the specific aspects of a distribution network (demand and pressure at each node, architecture of the pipe network, location and operation of waterworks and reservoirs, etc…). Here the results of a real case study are presented to illustrate the effects of reduced water consumption on maximum water age at a large scale. The transferability of the results to other cases has not been investigated, and requires case specific modeling as particular features of distribution networks significantly influence water age.

The effects of reductions of mains water demand due to rainwater harvesting on maximum water age are simulated with EPANET on the distribution network presented in Figure 3.
Figure 2. The evolutions of percentiles displayed on Figure 4 suggest that the distribution of maximum water ages is globally shifted towards higher water ages with increasing RWSO. RWSO is limited to 40% in the Figure as the rainwater supply systems’ reliability becomes quite low for higher values.

The previous results provided an overview of rainwater use effect on water age at the scale of a whole distribution system. An in-depth examination of the effects of rainwater harvesting on sensitive demand nodes with excessive increases in water age is also of interest. Let us assume that 72 and 96 hours (3 and 4 days) are indicative threshold values of mains water quality, 4 days being the maximum admissible water age. Figure 5 presents the number of nodes for which maximum water age is less than 72 hours (respectively 96 hours) without rainwater use and those where age exceeds 72 hours (respectively 96 hours) when RWSO is 20, 30 or 40% of overall water demand.

When considering the extreme threshold of 96 hours, the effect of rainwater use is limited to a maximum of 74 nodes (i.e. 4% of the nodes) where water quality is altered for RWD = 40%. If the threshold is set to 72 hours, however, the number of nodes for which maximum water age is exceeded is a more significant part of the network (6 to 34% of the nodes). These results demonstrate the significant impact on water quality caused by large scale implementation of rainwater harvesting.

Increased water age would require reinforcing the disinfection strategy e.g. by creating supplementary chlorine injection points in the network or/and increasing chlorine concentration at waterworks outlets. However, this solution has limited potential as chlorine concentration must remain below a maximum limit (usually 0.1 to 0.3 mg/L) to avoid taste and odor problems and the formation of carcinogenic disinfection by-products (Munavalli & Mohan Kumar 2003). Another possibility to tackle water age increase consists in flushing some sections of the distribution network. However, this solution is unlikely to be acceptable within a water saving policy.

A possible, but expensive solution to globally reduce water age in distribution networks involves the delivery of a fire defense strategy by dedicated infrastructure (not relying on the distribution network) in order to reduce networks pipes size.

Economic assessment

Economic assessment of rainwater harvesting practices requires the determination of the monetary value of water. From a private consumer perspective, the value of water is determined by the tariff structure of public water service: in France, the average cost of water is around 3€/m³. However, water price mainly covers fixed costs of financing, operation and maintenance of large infrastructures (waterworks, reservoirs, distribution network…). The actual marginal cost of production of potable water is in general very low (0.1 to 0.5€/m³).

From a broader perspective (at community scale), and in contexts where a potable water service already exists,
rainwater harvesting systems are only cost effective if the cost of production of rainwater is less than the marginal cost of production of potable water. In developed countries where water infrastructures are globally efficient, rainwater supply systems reduce the amount of water drawn from centralized potable water systems, but are generally not reliable enough to reduce reliance on centralized systems. In these cases, rainwater harvesting is not economically attractive. However, rainwater supply systems are economically feasible when the marginal cost of production is very high, e.g. if they enable the deferment of investment in new (or replacement of existing) mains water infrastructure, or where there is a cost for natural water abstraction due to acute scarcity.

**CONCLUSION**

Investigation of rainwater supply systems in various urban and climatic contexts show that supply reliabilities close to 100% with reasonable tank sizes could only be achieved when the ratio roof area to rainwater demand is high and under a homogeneous pluviometric regime (north-western France). With a RWSO of 30% and supply reliability of 95%, a 100 m² detached house with four occupants requires a tank volume of 6.5 m³ in Dinard compared with 26.2 m³ in Nice.

Widespread implementation of rainwater harvesting is shown to disturb the operation of mains water production and distribution systems because it increases the frequency and amplitude of the highest daily variations of mains water demand. Moreover, large scale models of a real distribution network show that rainwater use-related reduction in mains water demand has a significant impact on water age, and may lead to a lower water quality. A global water age increase can be mitigated by separating fire fighting capacity from the water supply distribution network so that pipe size can be decreased.

Finally, rainwater harvesting may be profitable in a context where the capacity of water supply infrastructure is exceeded by demand, and where rainwater use may defer or prevent building new mains water infrastructures.

**REFERENCES**

Circulaire interministériel no 465 1951 Interdepartmental bill no 465, dated 10/12/1951.


