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Optimization of Retention Ponds to Improve the Drainage System Elasticity for Water-Energy Nexus

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Abstract The purpose of this paper is to investigate the optimization of retention ponds for energy production by a low-head hydropower converter towards smart water grids and new flood adaptation solutions. Flood drainage systems are infrastructures essential in urban areas to control floods, which include retention ponds that can be used as innovative solutions adapted to climate changes and smart water grids to produce energy in a near future and to improve the drainage system elasticity. A catchment-scale water/energy management model is used for designing solutions by defining the characteristics of the urban area and the hydropower converters. The study area is based on Alcântara zone, in a district of Lisbon, a specific down-town zone close to the Tagus river, which has the backwater sea tidal influence. A solution based on the catchment of this area for extreme values of runoff induced by a significant climate changes event in these last years is analysed and then optimized in terms of energy production for different characteristic parameters. Finally, results are shown and discussed to reveal the most suitable solutions.

Keywords Retention ponds · Flood adaptation · Drainage system elasticity · Smart water grids · Water-energy nexus

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1 Introduction

Water and energy define some of the basic needs of modern societies. Several authors have presented global-scale water and energy foot-printing analyses (Hoekstra et al. 2009). Energy and water systems have traditionally been managed separately (Lindström and Granit 2012). Specialized decision support tools have been developed for both energy and water systems, independently envisaging the future smart water grids (Beaulieu 2010; Howe and Mitchell 2012). Only very few studies have attempted fully coupled analysis of water and energy systems and no one for stormwater and energy combination.

Joint management approaches and analyses will contribute to define a relative dynamic value of urban drainage water and energy, which is particularly relevant in a context with increased scarcity of primary resources, increased penetration of renewable energy sources and climate changes (Bizikova et al. 2008), outlining development strategies that will enable to minimize the future smart cities' vulnerabilities based on a sustainable, adaptation and mitigation (SAM) of vital infrastructures.

The control of floods is more and more serious challenge in growing urban areas (Tingsanchali 2012). The concern about drastic climate change makes this issue more and more important (Wegehenkel and Kersebaum 2008; Einfalt et al. 2009). Indeed, the urban flooding causes damage in people's life and in the economy of a region. As reported by (Santos 2011), traditional drainage systems installed to prevent flooding, had to be reviewed because they lead to an increasing of impermeable areas. The new urban drainage systems, called sustainable, use techniques as retention ponds and simulations to allow better control of water drained (Lee et al. 2012; Breinholt et al. 2008; Pender and Néelz 2007; Andoh 2012).

Hydro-energy production is sensitive to the total runoff, the timing of runoff, and the retention pond capacity. Under projected temperature increases, hydroelectric supply will improve in winter, but face challenges in summer (Sommers 2004; Bruno et al. 2008; Wiemann et al. 2009). The development of hydropower converters for low head differences has been in progress. The European project HYLOW gathers studies of new systems to exploit the energy created by small waterfalls or in water supply systems. Two of them will be brought up within the framework of this study. Firstly, a hydraulic pressure machine (HPM), which has been developed at the University of Southampton in the UK (Senior et al. 2008), is a wheel working for small heads 1 to 2.5 m and flow values between 1 and 2 m^3/s, depending on the size of the machine. As alternative to this device, under other available range of application, a tubular propeller with 5 blades (TP5B) developed at the Instituto Superior Técnico, Technical University of Lisbon is suitable for heads between 0.5 and 25 m and flow values in the range of 6 to 155 l/s, depending on the size of the machine (Ramos et al. 2009, 2012c). These new technologies can be applied to existing water systems, with the purpose to produce energy (Ramos et al. 2009; Madsen et al. 2009). Drainage systems are the ones of forthcoming possible applications. They lead with low-power values but with significant low-costs of installation and maintenance, which make them largely suitable, attractive and a sustainable solution.

The purpose of the following study is to optimize the production of energy at the outlet of a retention pond by a micro-hydro converter appropriate to available head and discharge. The analysis is based on the establishment of a power target demand considering the volume, the shape, the depth of retention ponds and the control of the outlet flow discharge. Retention ponds are implemented to control floods from a catchment, as well as hydropower stations are inserted at the outlet of each pond. A rainfall-runoff modelling is used to analyse runoff time series, being previously calibrated for this study area (Ramos et al. 2012a). The study is set in Alcântara, a district of Lisbon, which has facing in these last 10 years serious

Fig. 1 Example of recent flood events in Alcântara zone

problems of floods associate to climate changes, urban paved areas incremented and additionally to be a down-town area, close the Tagus river and the tidal effect of the Atlantic sea (Fig. 1).

Since the use of retention ponds or specific reservoirs involved with flood risk assessment is documented in several references (Eum et al. 2012; Talukdar et al. 2011), the combination of flood control with energy generation is the considerable novelty proposed in this research study. A real innovation consists in the introduction of the concept of conditional stormwater drainage system elasticity, which corresponds to new management methods and design implications permitting to maximize such conditional elasticity in favour of water/power systems' joint management. So the goal is to size both the volume and the pond shape in order to be able to maximize the energy production from available flowing stormwater that would be wasted.

2 Suitable Micro-Hydro Solutions

Retention ponds permit to manage water and to handle stormwater and can be used to implement hydropower stations. Individual reservoirs or retention ponds can be used to simulate and optimize the efficiency and elasticity of drainage systems by operating rules to storage stormwater. Power stations are presented in the simulation model as hydropower nodes supplied with water by retention ponds. Power stations limit the water flow and helps in damping and preventing flood event occurrences in urban areas. Hence, it is possible to specify the installed capacity of power station in hydropower nodes, the minimum available head and the target demand, which defines the available energy potential.

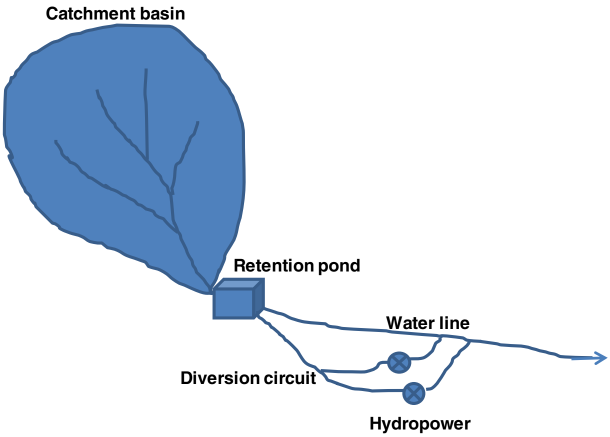
The study is based on two possible hydropower stations which are located at downstream of the analysed retention pond (Fig. 2). Power outputs are calculated as function of the outlet discharge and the net head from the water level inside the pond and the performance of the hydraulic machinery (η), as shown in the following Eq. 1.

$$P = \gamma Q H \eta \tag{1}$$

being P the power output, Q the turbine discharge and H the available net head.

The power Target demand is considered for each hydropower station. The first one (H1) has the priority over the second one (H2) and stated as a constant power output. For the second one (H2), the target demand is monthly variable depending on the season.

Fig. 2 Simplified representation of a retention pond and hydropower-base system



Integrated in the EU-HYLOW project developments, a novel hydropower converter for open channel flows and very small head differences of 1 to 3 m and flow rates of 1 to 2 m^3/s with 1.5 m of width had been developed at Southampton University in cooperation with the Technical University of Darmstadt (Senior et al. 2011; Schneider et al. 2011) (Fig. 3). A theoretical approach was developed to assess the performance characteristics of a Hydrostatic Pressure Machine (HPM) which will be applied in this research.

The following results can be summarised, as follow:

- diagonal blades mounted in an angle of 20° on the hub were identified as the best combination of simple geometry and efficiency;
- a flume width ratio of approx. 1:1.3 is recommended as most efficient and economic set-up;
- minimizing the gap between the tip of the blade and the curved bottom section, a flexible rubber band increases the available power output and the efficiency significantly;

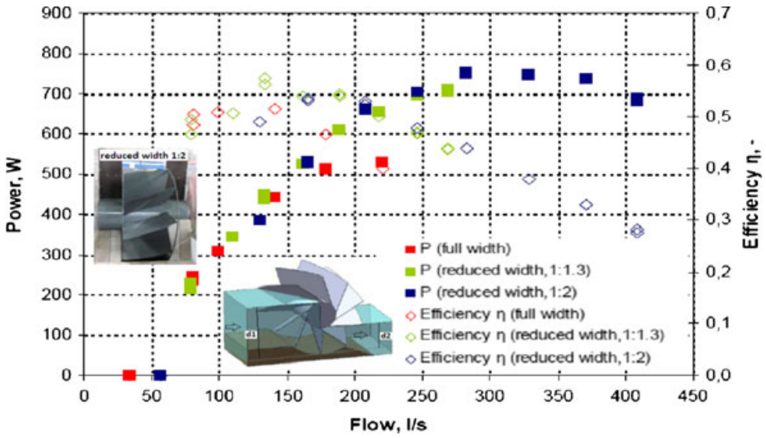


Fig. 3 Performance curves obtained in lab: diagonal blades with different ratios of HPM to flume width (all standardized to full width of 0.97 m); d1=0.815 m, d2=0.2 m

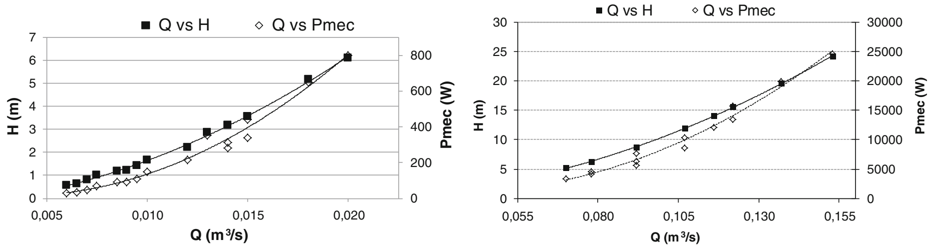


Fig. 4 Performance curves obtained by CFD simulations: tubular propeller with internal diameter of 100 and 200 mm

- an increase in head difference between the up- and downstream water levels results in a significant increase in power output and efficiency. Even if the upstream water level is slightly higher than the top edge of the hub (about 1/4 of the blade length) the power output and efficiency of the HPM improve.

As an alternative solution for lower available discharge values, a tubular propeller with five blades can be applied in a pipe system which has been developed at Instituto Superior Técnico-CEHIDRO, in the Technical University of Lisbon (Ramos et al. 2009, 2012a, b; Caxaria et al. 2011). A theoretical approach was developed to assess the performance characteristics as shown in Fig. 4 obtained based on CFD simulations, which allow to compare head and mechanical power for two different tubular propeller internal diameters (i.e. 100 and 200 mm).

Under lab conditions and for the internal diameter of 100 mm (with n_{spt} (m, m^3/s)= 238 rpm or n_{spt} (m, kW)=118 rpm) the tubular propeller with 5 blades (TP5B) was tested for different head and flow values, in order to simulate the conditions found in a real water system (Fig. 5). For power generation purposes, a 500 W with a DC permanent-magnet machine was also used.

The use of theTP5B in water pipe systems has demonstrated good hydro-mechanical efficiency values (40–70 %) and it represents an interesting solution to be used for available flow energy that would be dissipated or wasted.

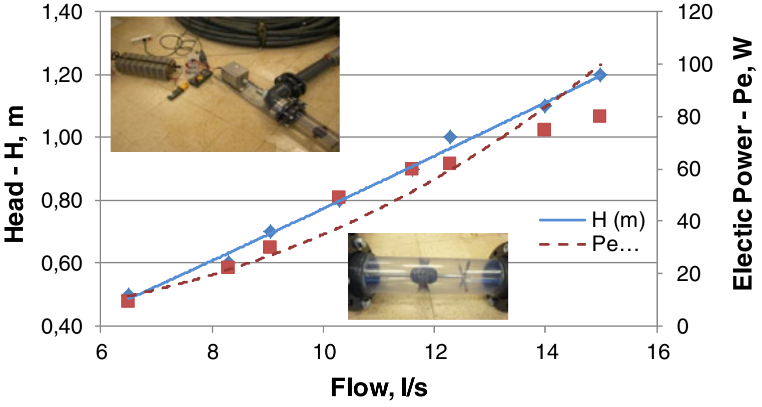


Fig. 5 Performance curves obtained in lab conditions for D=100 mm with a DC permanent magnetic generator connected

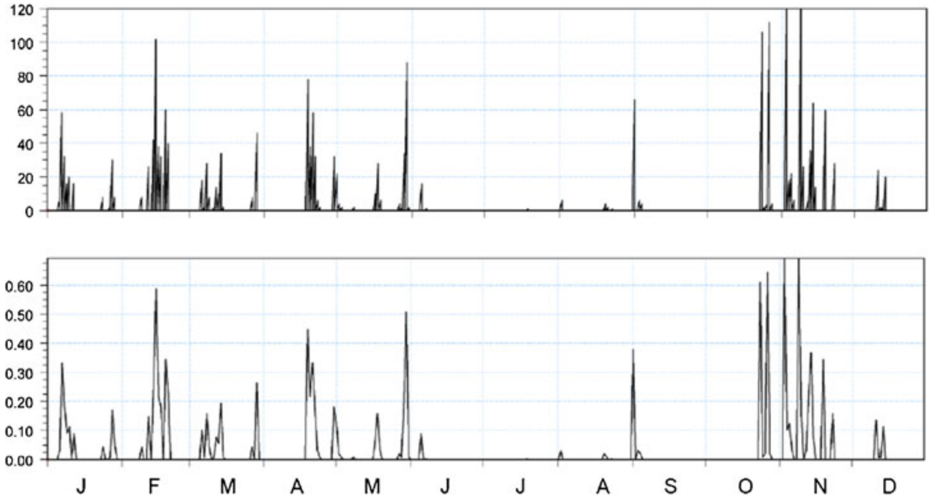


Fig. 6 Rainfall (mm) (top) and runoff (m^3/s) (bottom) for 0.05 km^2 Alcântara catchment area for average year

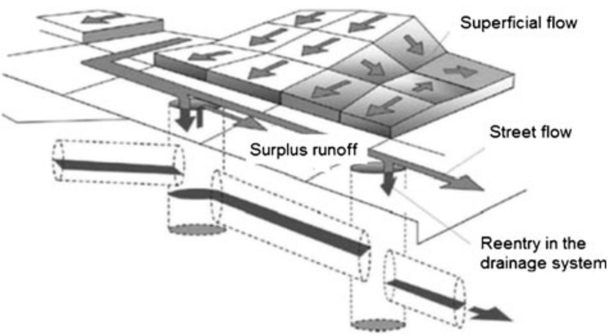
3 Methodology

The first step of the study consists on identifying the influence of micro-hydro installation in drainage systems with storage ponds to find out the best set-up to optimize the power generation. Furthermore, at the same time, retention ponds can control floods. Thus, according to a target demand, the water level and the power output are defined as a function of the pond volume.

The selected heads correspond to a use of a wheel hydropower converter or a tubular propeller in order to take account to their respective ranges of application. For this propose the rainfall and the size of urban area are defined. For the selected study zone the size of the area is set at 0.05 km^2 and the rainfall was taken into from the climatological Lisbon station, based on specific climate change scenario events occurred in the last 10 years. In Fig. 6 rainfall and runoff graphs are presented (Meteo.pt 2012).

Figure 7 shows the typical dynamic flow scenario in a complete drainage system composed by superficial and underground pipe flow. The risk of flooding in urban areas is directly related to the capacity of the sewer system to convey or hold the excess runoff generated by a particular rainfall event.

Fig. 7 Type of flow in a typical drainage system



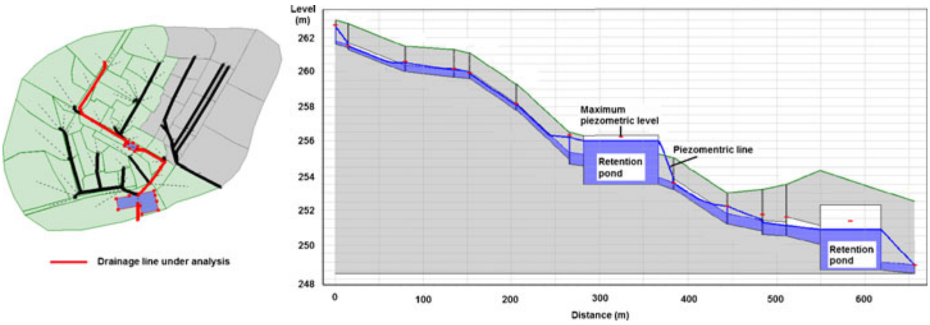


Fig. 8 Flood retention ponds in Alcântara drainage systems: catchment basin and evaluation of the piezometric line along the drainage system

Accurate modelling of these systems is a fundamental tool for real time management, enabling operators to take advantage of the systems full capacity and minimize flooding. Storm Water Management Model (SWMM) is a dynamic rainfall-runoff model (Fig. 8) for the analysis of flooding in urban areas and the evaluation of the performance of different mitigation measures for its prevention. The component of runoff operates on a collection of sub-catchment areas that receive precipitation and generate flow.

The volume and shape of retention ponds are considered to lead the best configuration in terms of storage and energy production. In Fig. 8 the drainage line is presented, where two retention ponds should be installed (one in the middle of the drainage line and another at downstream). Quadrangular and a trapezoidal shape configurations are examined. Figure 9 presents the area and volume variation in these two cross-area shapes, as well as the retention solutions for gardens storage modular cells for micro-hydro implementation.

The urban flooding, from storm rains, has special importance due to the impacts they cause in people's everyday lives and economic activities in view of its fast

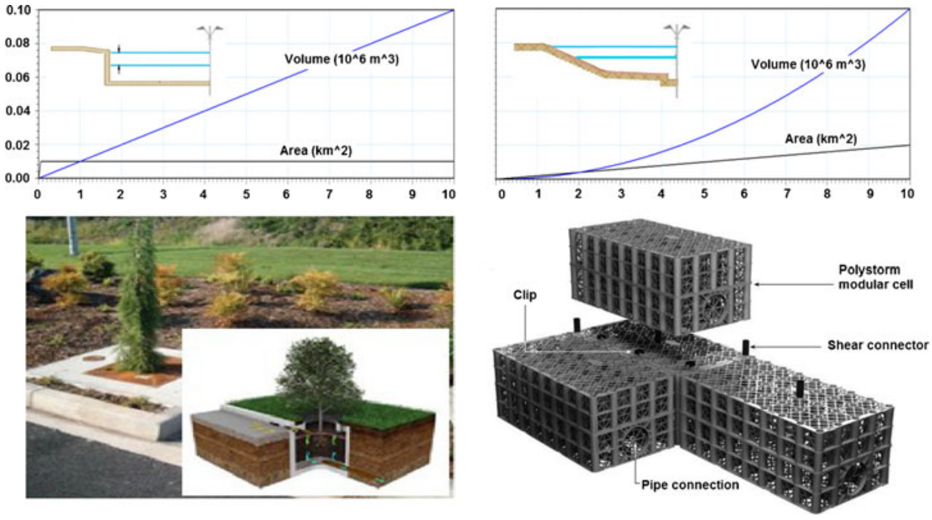


Fig. 9 Area and pond volume variation (*top*) for quadrangular (*left*) and trapezoidal reservoir (*right*); real retention pond solutions (*bottom*) for gardens (*left*) using storage modular cells with pipe location connection for micro-hydro implementation (*right*)

Table 1 Characteristics of micro-hydro converters

	TP5B (D=100 and 200 mm)	HPM (1.50 m width)
Head	Low head <25 m	Very low head <2.5 m
Discharge	Small flow from 0.007 to 0.155 m^3/s	Medium flow about 3.6 $m^3/s/m$ width

action. The unsustainability of the traditional drainage systems is the main reason for the increasing of paved areas, leading to a need to review the entire old systems. Thus unconventional drainage systems arise, also known as sustainable urban drainage systems, which differ from the traditional concept to optimize and adapt the solutions to new realities. These systems using techniques of flow delay, detention, retention and infiltration allow greater control over the quantity and quality of water drained, preventing the flood areas may affect the functionality of urban zones.

4 Results

The target demand corresponds to a constant value of output power for the hydropower station 1 (H1) and a variable value, limited by the maximum power of H1, for the hydropower station 2 (H2), depending on the season according to the monthly evolution. This analysis is developed by investigating the evolution of the power output by each hydro system, the total generated power and the water level variation, as function of the retention pond volume. The purpose is to obtain the influence of the elasticity of the drainage system by a joint management of runoff water and energy production to find the best parameters for the pond volume, in order to optimize the total energy production.

The proposed energy converters will use low heads. Each hydropower system has its own characteristics regarding the head and the discharge, as presented in Table 1.

For the analysed case study, the tubular propeller seems more suitable to the drainage system, because the low flow values allow a more continuous energy production along the all year. Its main characteristics are presented in Table 2. The maximum mechanical power is the power capacity of the hydropower station and the flow is limited to 0.15 m^3/s to keep the turbines on its range of application. Hence, the more appropriate conditions to exploit the entire capacity of the installed hydropower are then analysed.

The surplus capacity is allowed in the simulation, which means the production can be superior to the demand, as flows into the outlet are inferior to 0.1 m^3/s. First, the results for a quadrangular cross-section pond, as the usual shape for a typical storage tank, are presented. Then, the influence of the shape is discussed by comparing a quadrangular shape with a trapezoidal one.

Table 2 Characteristics of tubular propeller applied to the case study

	H (m)	Q (m^3/s)	Pmec max (kW)	η max (−)
Reservoir	10	0.05–0.1	5–12	0.8

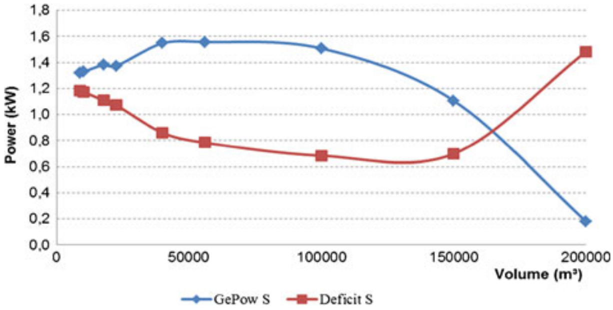


Fig. 10 Total generated power and power deficit as function of the pond volume

i) Analysis for a quadrangular shape pond

Figures 10 and 11 represent respectively the total generated power and deficit, and the flows through hydropower outlet and river. The maximum generated power becomes apparent for a volume between 50,000 and 100,000 m^3, which is equivalent to 1.6 kW output power. The loss flow to the river becomes negligible compared with the total flow turbine discharge. The flows through the power station outlet present an average value about 0.015 m^3/s (Fig. 11).

Figure 12 shows the water level variation as a function of the pond volume. The global behaviour inside the pond shows the maximum water level does not correspond to the maximum of energy production.

ii) Comparison for two different pond shapes

The variation of turbine flow in hydropower stations 1 and 2, respectively, are presented in Figures 13. Quadrangular pond shape induces higher flow variation than the trapezoidal one, regarding the power demand imposed, as a restriction of the objective function to maximize the energy production.

Figure 14 presents the comparison of total power output or quadrangular and trapezoidal pond shapes. The trapezoidal shape allows creating a bigger amount of energy for the same pond volume due to the higher head for the same turbine volume as presented in Fig. 15, which shows the water level variation inside the reservoir.

Besides, the maximum generated power is larger with the trapezoidal shape, it means that the choice of right volume can be lesser important to get the maximum power production. However the volume could be interesting if rainfalls are very changeable year by year.

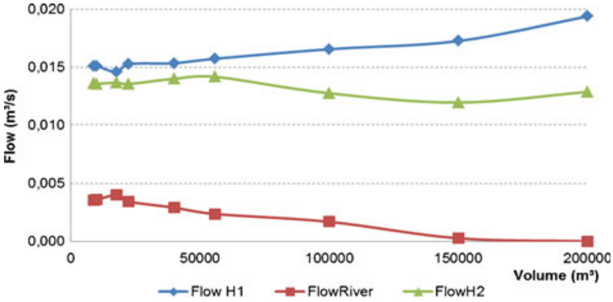


Fig. 11 Flow through the hydropower stations and the river as function of pond capacity

Fig. 12 Water level variation as function of the pond volume

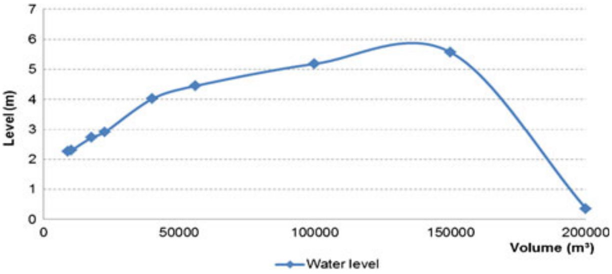


Fig. 13 Turbine flow variation in hydropower station 1 (H1) and 2 (H2) as function of pond volume for two different shapes

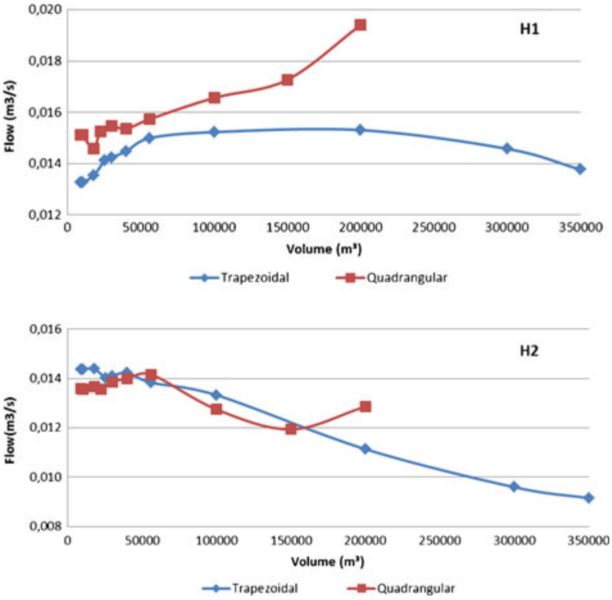


Fig. 14 Total generated power as function of pond volume for two different shapes

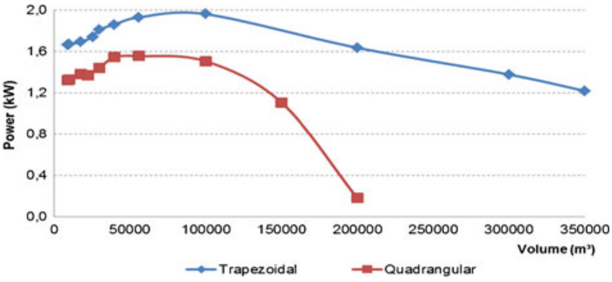
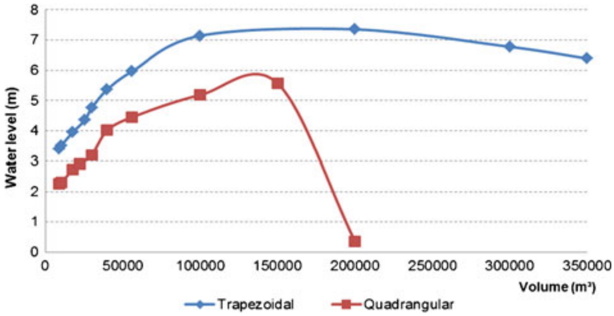


Fig. 15 Water level as function of pond volume for two different shapes



5 Conclusions

The study gives some clear results about water-energy nexus solutions for urban drainage systems based on flood retention ponds towards future smart water grids. These can be promising solutions, where the importance of the drainage system elasticity can change the actual paradigm of flood adaptation/mitigation. The runoff, which can be a problem, has become a new energy source with several advantages for the social environment of urban areas. This new water-energy prototype can be implemented in existing runoff systems or in forthcoming urban design solutions.

In the analysed solutions, higher the water level in the pond for the same volume better is the production of energy, because the available head is higher for the same turbine discharge. Indeed, flow values depend on rainfalls, so the control is operation-rainfall-runoff dependent. Likewise the shape of the pond has a significant impact, but depends on territory arrangement.

Then, there is a volume of the reservoir for which the solution is optimized whatever the set parameters and mostly, a pond volume interval could be set as the range of system operation.

Besides, the target demand should be adjusted regarding rainfalls and all system characteristics. A special effort of optimization is required to maximize the generated power and minimize the power deficit. Finally, the control of the water level was proved essential. Indeed, the reduction of the target demand according to the allowed water level improves considerably the energy production because the head difference is kept high. The study reveals this system could produce about 17.5 MWh/year in the optimized scenario (for an average year hourly power of 2 kW, for a trapezoidal pond shape). It should be noticed that the main purpose of the system is the flood prevention of urban areas, which can also be combined with the energy production. Hydropower solution contribute to slow down the flow out of ponds which allow preventing floods with damage potential at downstream, damping the fast flow wave's propagation.

It is important to highlight this integrated methodology for hydraulic simulation, optimized low-cost hydro solution and flood real-time control/adaptation in a coupled stormwater-energy innovative solution, which can improve the drainage system elasticity using retention ponds of urban areas, in a regional scale. The methodology operates in a dynamical framework, depending on the pond volume and shape, rainfall-runoff values and hydropower characteristics.

On the industrial side, the objective is to develop leading expertise in integrated management strategies (of water and energy), in a new perspective of the so-called future smart water grids based on new sustainable stormwater-power solutions improving the elasticity of urban water systems. These solutions have taken into account the control and adaptation of a joint management of flood-energy drainage systems under renewable innovative energy policy goals, particularly concerned with the goal of non-carbon emissions, as well as reaching a more and more share of renewable energy sources in a near future. Within technical constraints, water-related storage in flood ponds can be scheduled flexibly, allowing for appropriate stormwater/energy storage solutions.

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