Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

Management tools for hydro energy interventions in water supply systems

Jos Frijns[a,*], Enrique Cabrera Marchet[b], Nelson Carriço[c], Dídia Covas[c], Antonio J. Monteiro[c], Helena M. Ramos[c], Andrea Bolognesi[d], Cristiana Bragalli[d], Sotiria Baki[e] and Christos Makropoulos[a,e]

[a] KWR Watercycle Research Institute, P.O. Box 1072, 3430 BB Nieuwegein, The Netherlands

[b] ITA Universitat Politecnica de Valencia, Edificio 5C Camí de Vera, s/n, UPV, 46022 Valencia, Spain

[c] Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisbon, Portugal

[d] Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Via Zamboni, 33, 40126 Bologna, Italy

[e] Department of Water Resources and Environmental Engineering, National Technical University of Athens, 5, Heroon Polytechneiou, 157 80 Athens, Greece

*Corresponding author. E-mail: jos.frijns@kwrwater.nl

Abstract

There is significant potential for energy recovery through the use of micro-hydropower installations in water supply systems (WSS). To exploit the full potential of hydro energy in balance with the optimal hydraulic performance and water supply service, multi-objective management tools are needed. This paper presents the application of four management tools: (1) an energy audit to evaluate the potential hydro energy in the water pressurised systems of Alcoy; (2) multi-criteria decision-making methods for the selection of the preferred energy-efficient operation of a system with a pump-storage reservoir and hydro-turbines in the Algarve; (3) a numerical dynamic tool for optimal turbine operation in the water distribution of Langhirano; and (4) an urban water optioneering tool to estimate the hydropower potential of the external aqueduct network in Athens. These methods showed that through an integrated approach the WSS can be optimised for both hydraulic performance and hydro energy production.

Key words: hydro energy, multi-objective management tools, water supply system

INTRODUCTION

In response to climate change and rising energy costs for operation of water supply and treatment, the water sector is aiming to become more energy efficient. There are numerous options for energy measures in the water sector ranging from water conservation and process efficiency improvements to new technologies and redesigning water systems. In many European countries, drinking water companies have implemented energy-efficient production techniques and optimised distribution systems (Frijns *et al.* 2012). As pumps constitute the most part of the energy consumed in water supply systems (WSS), particular attention is paid to pump scheduling optimisation (Basupi *et al.* 2014), the use of efficient motor-pumps sets and optimised pipe and network designs (Vilanova & Balestieri 2014a). Cabrera *et al.* (2010) showed the substantial overall energy saving that can be achieved by leakage control in water distribution networks.

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

Next to energy efficiency improvements, there is a need for new concepts in which water is viewed as a carrier of energy, i.e. (waste)water as a source of chemical (biogas) and thermal energy (Frijns *et al.* 2013). In areas with high topographic gradients, in which water is transported by gravity, the high pressure in the water mains and distribution networks makes these systems capable of hydroelectric power generation (Ramos *et al.* 2011; Carravetta *et al.* 2012).

Within the Transitions to the Urban Water Services of Tomorrow (TRUST) project, intervention concepts for energy saving, recovery and generation from the urban water system have been investigated in 8 case studies in 7 European pilot areas (Frijns 2014). In this paper, the results are presented of 4 case studies dealing with micro-hydro technologies in WSS to convert energy from the pressure and flow into electricity. Emphasis is put on the management tools applied to optimise the operation and energy balance of WSS.

Optimisation tools for hydro energy in WSS

Micro water turbines are being applied in WSS in locations where there is an excess of available hydraulic energy (Gonçalves *et al.* 2012). At these locations, pressure reduction valves (PRVs) are commonly used to control the maximum pressure in the WSS. As an alternative and sustainable solution to PRVs to control network pressure and produce energy, pumps operating as turbines (PATs) can be applied. While PRVs reduce the pressure through the dissipation of energy, PATs can convert the excess pressure into electricity. Besides that, WSS with free flow channels can generate hydro energy through turbines.

Although significant potential exists for energy recovery through the use of micro-hydropower installations in WSS, its application in practice is still under development (Vilanova & Balestieri 2014b). The anticipated positive economic results are not always evident (Ramos & Ramos 2009). The recovery of hydro energy from WSS is highly variable depending on the topography and layout of the system. Complexities such as variations in flows and turbine efficiency should be considered (McNabola *et al.* 2013).

Moreover, a balance needs to be struck between the hydraulic performance, energy efficiency and costs. The current optimisation techniques to improve the design of WSS seek to define the optimal solutions in terms of investment costs. It is, however, preferred that the operation of WSS is optimised for both hydraulic and energy efficiency. Needed are multi-objective optimisation techniques to carry out simultaneous energetic and economic objectives (Ramos & Ramos 2010; Vilanova & Balestieri 2014a).

The optimal hydro energy intervention in WSS can be accomplished by hydraulic simulation, based on the hydraulic characteristics and the mass and energy balances. The energy balance of WSS is highly site-dependent, thus requiring a systematic energy analysis to evaluate separately the influence of pumping, the layout of the network, water loss through leakage and the hydro energy potential (Lenzi *et al.* 2013). Preferably, the hydraulic simulation and energy balance is followed by an optimisation module composed of genetic algorithms to determine the optimal solution, e.g. maximisation of energy use while maintaining sufficient pressure (Araujo *et al.* 2006).

This paper presents 4 optimisation methods to assess the hydro energy potential in WSS. All methods have an integrated approach towards both the hydraulics and energy:

1. Energy audit to evaluate the energy efficiency and the potential hydro energy that can be recovered from a water pressurised systems transport in Alcoy (Spain).
2. Multi-criteria decision-making methods for the selection of the preferred energy-efficient operating water supply scheme, consisting of a pump-storage reservoir with hydro-turbines, in the Algarve (Portugal).
3. Numerical dynamic tool for optimal turbine operation as part of integrated pressure and energy management in WSS of Langhirano (Italy).

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

4. Urban water optioneering tool (UWOT), that simulates demand and supply of the urban water cycle, to estimate the hydropower potential of the external aqueduct in Athens (Greece)

The 4 methods and cases are presented in the following sections. Each section consists of a description of the management tool, the case study, the main results and a conclusion.

ENERGY AUDIT OF WSS

The aim of an energy audit is to evaluate how much energy is consumed and to identify measures that can be undertaken to reduce consumption, to use energy more efficiently or to produce energy. Performing energy audits in WSS is, therefore, a crucial step to improve its energy efficiency. The Alcoy case presents a methodology for a water and energy audit to discover what parts of a water pressurised systems transport have the greatest improvement margins and which displays the potential hydro energy that can be recovered.

Energy audit methodology

This section presents the energy audit of a water network which is obtained from the energy equation in integral form, and its time integration extended over a given period. This energy audit requires a previous water balance and the mathematical model of the network, both of which are necessary to know the energy flows through the system's boundaries. The audit allows accounting for all the energy in the system. From the energy performance indicators, it is possible to identify the improvement actions that will make the system more efficient, looking both at energy saving and recovery of topographical energy (Cabrera *et al.* 2010).

As the energy linked to water pumping can be quite substantial, an efficient water pressurised transport is needed. The critical point to be efficient is to know where we are and where, ideally, could be and where, with the available technology and the economic framework, it is realistic to arrive. For such purpose three new indicators are defined. The first two indicators are the ideal and real efficiencies of the system (η_{ai} and η_{ar}, respectively) and reflect the values of the minimum energy required by users – the minimum amount of energy to be supplied to the system (given its ideal behaviour) and the actual energy consumed. The third indicator, $\eta_{ar,o}$, is the energy performance target and it is estimated by setting an ambitious but achievable level of energy loss due to inefficiencies in the system (pumping stations, leakage, friction loss and others). The information provided by these three key performance indicators makes a significant contribution towards increasing system efficiency. The real efficiency indicator shows the actual performance of the system; the energy performance target provides a realistic goal on how the system should be performing; and finally, the ideal efficiency provides the maximum and unachievable level of efficiency (limited by the topographic energy linked to the network topography). Details of the three indicators are defined in Cabrera *et al.* (2014).

If the improvement margin ($\eta_{ar,o-}\eta_{ar}$) calculated with the tool is deemed relevant, it should trigger the subsequent stages in the process. The first being a water and energy audit (Cabrera *et al.* 2010) to discover which parts of the WSS have the greatest improvement margins and which present the best cost-benefit opportunities. Furthermore, in systems with an irregular terrain in which topographic energy is significant, the recovery of this energy should be explored – and if found to be unviable then the overpressures should be neutralised with PRVs.

Although in this short description just two stages of the whole process (see Figure 1) are described (diagnostic and analysis), a more complete methodology (with five stages) is now under development. The other three stages are 'exploring the actions' to improve the efficiencies, 'taking actions' selected after a cost-benefit analysis from the explored ones and a final 'label' of the whole system that should be a global mark that weights the different efficiencies of the system as a whole. It is important to

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

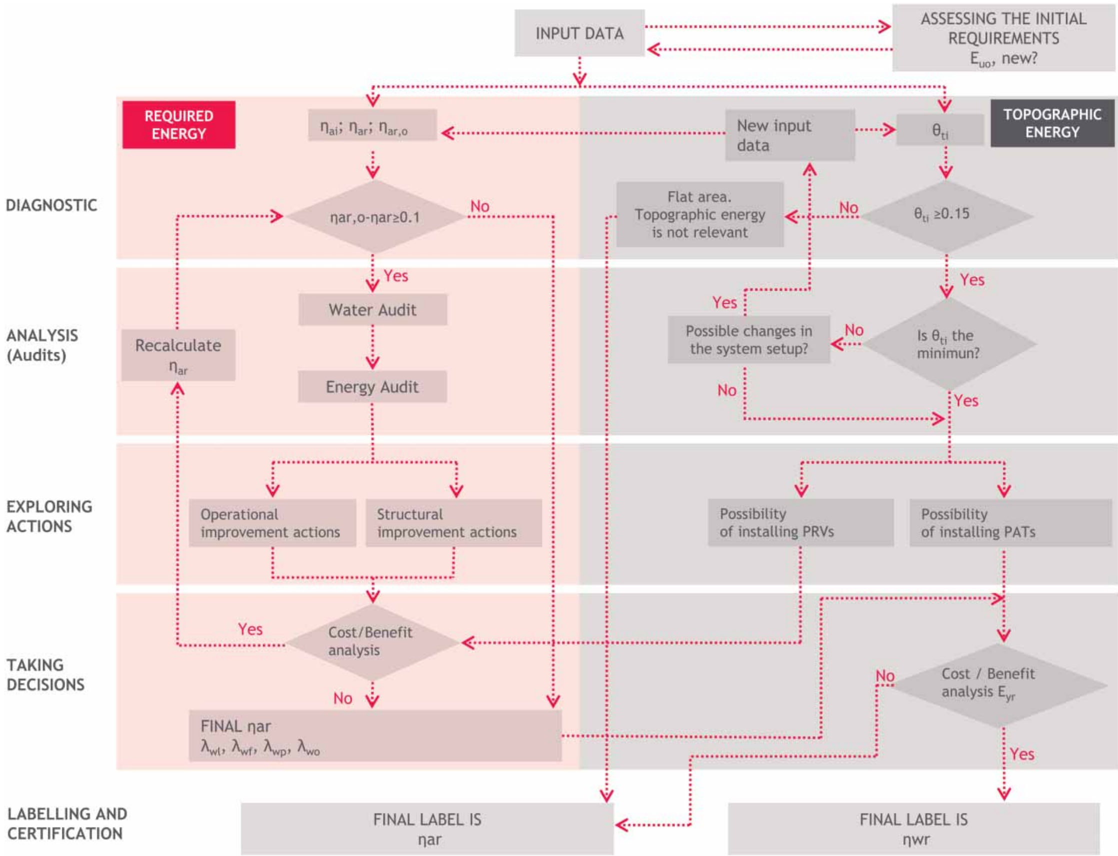

Figure 1 | Flow chart to improve the efficiency in water pressurised systems.

underline (Figure 1) that the energy required process (left column) follow a different way to the topographic one (right column).

Case study Alcoy

Alcoy (Spain) is a hilly city located 100 km south of Valencia and 60 km north of Alicante. Its population is 50,000 inhabitants, feed through 6,000 connections. The network length is 182 km and has been mathematically modelled without simplifications, that is to say, all node connections have been kept in the model. The result is a model with 10,514 nodes and 10,872 pipes. That makes it particularly precise and simple to model the load, because there is a unique and direct correspondence between the water metered and billed and the network's node. This feature is particularly relevant in seasonal cities where summer demand is quite different to winter requirements. The highest node of the network is 754 m over the sea level while the lowest is just 466 m, with a difference of 300 m, giving an idea about its complexity. Water is supplied from three different injection points.

Main results

The global real efficiency η_{ar} is 0.41 while the theoretical one (η_{ai}) is 0.52. Its difference 0.11, over 10%, indicates the global margin of improving that in this case exists. In Alcoy, where most of the energy supplied is gravitational (over 70%) losses have a reasonable value by two reasons. First because the current main losses term (pumping inefficiencies) is not significant (just 30% of water is pumped) and furthermore pipe friction is not relevant because the network is oversized. The target indicator is estimated at 0.46, an improvement that proceeds mainly from leaks reduction (see Table 1). By the other hand, the

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

Table 1 | Daily energy audit of the Alcoy network

Water energy audit (kWh/day)				
$E_{sr} = 8.623$ kWh/day		$E_{uo} =$		3.482 kWh/day
		$E_{tr} + E_{er} =$		620 kWh/day
	$E_{sr,n} = 6.016$ kWh/day	Water network losses	$E_{rl} =$	1.587 kWh/day
			$E_{rf\ (pipes)} =$	477 kWh/day
			$E_{rf\ (valves)} =$	1.527 kWh/day
			$E_{rp} =$	774 kWh/day
	$E_{sr,p} = 2.607$ kWh/day	$\Delta E_{\ (tank)} =$		156 kWh/day

Global system $\eta_{ar} = \frac{E_{uo}}{E_{sr}} = \frac{3482}{8623} = 0,4$

With E_{sr}, total supplied energy; $E_{sr,n}$, natural (gravitational) supplied energy; $E_{sr,p}$, shaft (wire) supplied energy; E_{uo}, minimum required energy by users; E_{tr}, topographic energy of the system; E_{er}, supplied excess energy; E_{rl}, reducible Erl (wasted energy in leaks); E_{rf} (pipes), reducible pipe's friction energy (pipe's friction wasted energy); E_{rf} (valves), reducible valve's dissipation energy (PRVs wasted energy); $\Delta E_{(tank)}$ daily variation of stored energy in tanks.

complementary value to the ideal efficiency (1- 0.52 = 0.48) is the topographic energy embedded in the water network. It is very high because, as said before, Alcoy is a very hilly city. Although theoretically all that energy could be recovered, in real systems just a few percentage (if any) of this total can be saved with a PATs. Table 1 depicts the global energy audit of the network.

Conclusion on energy audit

Table 1 clearly indicates where the main energy savings are located. Energy embedded in leaks (Erl) is 1,587 kWh/day, representing 19% of the total energy supplied. Friction losses in pipes are not significant, because the network is oversized. Cost-effective analysis of the different potential actions to diminish these values are required (see, in Figure 1, stages three and four). An analysis that is very much depending on the energy cost and, in the case of the Erl, of the variable water costs as well.

Energy lost in PRVs (Erf(valves) = 1,527 kWh/day) is a different issue, because the energy these devices dissipate is topographic and therefore cannot be saved, just recovered through PATs. In fact, in the case of Alcoy there is an appropriate location to install a PAT and the energy that can be daily recovered is estimated at 631 kWh/day. It is the result of an available head of 100 m, with an average flow of 80 l/s, an energy that actually is wasted (VRP friction).

In any case, the most important conclusion is not that the figures correspond to the Alcoy's analysis that is a very singular case. What is relevant is the complete methodology that has been conceived. It can help to improve in a significant way the efficiency of water pressurised system transport.

MULTI-CRITERIA DECISION-MAKING FOR EFFICIENT ENERGY OPERATION OF WSS

This section presents how, after having applied an energy audit, two multi-criteria decision-making methods aid in the selection of the preferred energy-efficient operating water supply scheme. The Águas do Algarve (AdA) case study includes a pump-storage reservoir in association with hydro-turbines that, in addition to guaranteeing continuous flow during daily operation, aims to reduce the external energy dependence and operational costs.

Multi-criteria decision-making methods

The case study aims at the analysis and discussion of the most efficient energy operating schemes in a WSS, taking into account the seasonal variation of consumption. The traditional single criteria decision-making approach, usually aiming at the cost minimisation, has shown to be inadequate to

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

address this issue, as it does not take into account the technical performance of the system nor social and environmental aspects. Multi-criteria decision analysis (MCDA) was used, being a useful tool in the decision-making process to deal with a multiplicity of metrics and the complexity of energy planning projects (San Cristóbal Mateo 2012). Two multi-criteria decision-making methods have been applied. Results obtained by the two methods are discussed.

The main purpose of MCDA is to provide decision aiding tools that help finding solutions for real-world problems, most often, problems having conflicting points of view. Two multi-criteria decision-making methods have been applied by AdA for the selection of the best energy-efficient scheme of a water supply system, namely, simple additive weighting (SAW) and ELECTRE III.

The SAW method, also called as weighted sum method is one of the most widely used methods, in which the alternatives are ranked based on their weighted sum score (Tzeng & Huang 2011).

ELimination et Choix Traduisant la RÉalité (ELECTRE) methods are a family of MCDA techniques developed in France in the 1960s. These methods have been widely used in many real-life decision problems (e.g., energy, transportation, environmental and water management) and have proven to be suitable for situations in which at least five decision criteria are involved (Rogers & Bruen 2000; Figueira *et al.* 2005; Dias *et al.* 2006). The ELECTRE III starts by a pairwise comparison of each alternative to the remaining one, in order to accept, reject, or, more generally, assess the credibility of the assertion 'alternative a is at least as good as alternative b'. This method involves two stages: the construction of one or several outranking relation(s) followed by an exploitation procedure.

Case study Algarve

The case study is a WSS of the Eastbound of Algarve region in Portugal (Eastbound or Beliche system). The supplied population is 450,000 inhabitants from October to May, which triples in the peak of summer season. This system has one surface water source (Odeleite/Beliche reservoir) and water is treated in both Tavira and Beliche water treatment plants (WTP). At the upstream of Beliche WTP, there is a micro-hydropower plant with two pumps-as-turbine installed. The system downstream Tavira WTP has four pumping stations, four in-line storage tanks and delivers water to 20 municipal tanks. It is composed of 115 km of pipes with diameters from 40 to 1,500 mm.

The system has two operating schemes due to the seasonality of tourism:

- OS1 – Operation Scheme 1, in which only Tavira WTP is operating and water is conveyed from Beliche to Tavira by a 28 km raw water main with two pumping stations.
- OS2 – Operation Scheme 2, in which 78% of water is treated in Tavira and 22% in Beliche WTP and the microturbine is operating.

Several metrics have been selected for assessing energy efficiency, associated to performance, cost and risk, namely:

- E1 – energy in excess per unit of the revenue water (kWh/m^3);
- E2 – ratio of the available energy in excess (-);
- E3 – greenhouse gases produced from energy use (kgCO_2eq/m^3);
- E4 – energy production profits (€/m3);
- E5 – consequence of a failure in Tavira's WTP (%).

The aim of this analysis is to compare the energy efficiency of the Eastbound system for two operating schemes using the referred energy metrics and two different demands scenarios: high season (HS) and low season (LS) demand scenario. Four situations were simulated: OS1-HS, OS2-HS, OS1-LS, OS2-LS. An energy audit was performed according to Cabrera *et al.* (2010) and Souza *et al.* (2011), i.e. the energy balance was calculated using the hydraulic model.

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

Main results

Table 2 shows the results of the energy audit obtained. Weights were attributed by a panel of technical specialists of the water utility considering three points of view: environmental (E1, E2 and E3), financial (E4) and social (E5). At first sight, the best option seems to be OS2-LS (78% of water treated in Tavira and 22% in Beliche) and the worst OS1-LS.

Table 2 | Results of the energy efficiency metrics (decision matrix)

Alternatives	E1 (kWh/m^3)	E2 (-)	E3 (kg CO_2eq)	E4 (%)	E5 (%)
OS1-HS	0.27	1.37	161.5	0	100
OS1-LS	0.29	2.06	80.9	0	100
OS2-HS	0.24	1.51	151.0	2.9	51.7
OS2-LS	0.23	1.83	67.5	6.3	47.6
Preference direction	↓	↓	↓	↑	↓
Weights	0.2	0.2	0.3	0.2	0.1

Results obtained by application of the two MCDA methods, SAW and ELECTRE III, are shown in Figure 2. The best option is OS2-LS followed by OS2-HS (in both methods) which means that it is better to have Beliche WTP working the whole year and not only at the HS. The main difference in the results is that, with ELECTRE III, the alternatives OS1-HS and OS1-LS are ranked ex-aequo which does not happen with SAW method. Results are coherent, since OS2-LS is better than all others options in at least four metrics.

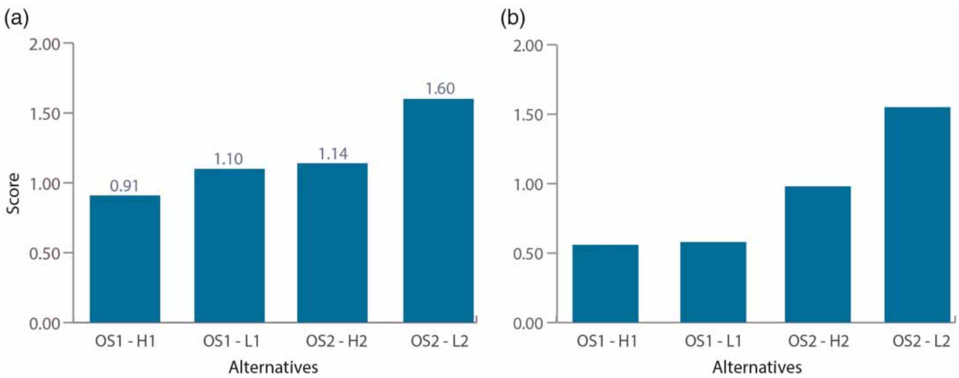

Figure 2 | Ranking obtained with: (a) SAW method; (b) ELECTRE III method.

Conclusion on multi-criteria decision-making

The application of the two multi-criteria decision-making methods has shown that the best option is Operating Scheme 2 with Low Season (LS) demand scenario (OS2-LS) which means that it is better to have Beliche's WTP working the whole year and not only at the High Season (HS). Moreover, the preferred Operating Scheme 2 includes energy recovery by a micro-hydropower plant with two pumps-as-turbine.

The main difference between the two methods lies with the two worst options since ELECTRE III gives an ex aequo rank and SAW does not allow this. Despite this difference, the methods give coherent results.

The problem of selection of an appropriate method for some type of problem is an open research issue. Before this selection, the problem should be carefully described as a not well-structured method

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

can restrict the application of MCDA methods. Structuring the decision problem is one of the most importance stages in the analysis and resolution of a multi-criteria decision problem.

The main drawbacks of the SAW method are adding or removing alternatives may change ranking; difficult to use for qualitative scales; and depends on normalisation used. The main advantage is that its simplicity allows using a normal spreadsheet to rank the alternatives. ELECTRE III is more complex than SAW method, which can use discrimination thresholds incorporating in that way the imperfect nature of the evaluations. Although on the one hand this is an advantage, on the other, it is a disadvantage because assigning values to these discrimination thresholds is not a trivial task.

NUMERICAL DYNAMIC TOOL FOR INTEGRATED PRESSURE AND ENERGY MANAGEMENT IN WSS

This section presents the development of a methodology for integrating pressure and energy management in WSS, with the aim to save both water and energy resources. The dynamic optimal turbine selector (DOTS) is presented as a numerical dynamic tool for optimal turbine operation in the WSS of Langhirano.

The WSS of Langhirano appears as a meaningful case study for the water-energy nexus: the system is almost completely supplied by pumps (high energy impact) and the most densely populated part of the network is already sectorised and organised in seven District Metered Areas (DMAs).

The research focussed on the presence of PRVs at the inlet point of each district, investigating how to recover energy from the existing pressure excess at the valves, as well as to save water through pressure management strategies. The method uses among others Genetic Algorithms to identify the optimal DMA boundaries and to determine the optimal type, location and setting of the PRVs (based on Awad *et al.* 2010).

This was done by integrating two main actions:

- Development of a numerical tool (accounting for the specific machine efficiency) in order to search for the optimal turbine/PAT to be installed in a certain point, leading to the highest amount of energy produced, given the flow and head patterns during the day.
- Assessment of the energy producibility under different operating scenarios of the WSS, considering both PRV settings and pumps' operation.

The DOTS tool

The basic parameters involved in the operation of a generic hydraulic turbine are: Hu (net available head), Q (flow), n (rotation speed), η (total efficiency). Such four values allow for calculating the effective power and the momentum of the turbine. Turbine performances are generally determined through experimental measurements and presented in a (n, Q) chart, called hill diagram, where Hu is kept fixed.

In the hill diagram for Francis turbines (selected as the most suitable for the energy recovery and micro-generation purposes), flow rate is influenced by the rotation speed of the impeller. The system can adapt itself through the degree of opening of the turbine distributor (OTD) and the flow rate diverted into the bypass valve (Qv). In practice, if the turbine is forced to operating conditions beyond its capabilities, the flow through the turbine (Qt) should be reduced and diverted through a bypass so as to ensure the passage of the flow rate required by users (Qu). Once Qt, OTD and Hu are known, the instantaneous efficiency and power generated can be derived, together with the energy produced by the system.

The logical scheme of the simulation tool is shown in Figure 3.

The conceptual model described above can be applied to any desired time series. Two time series are required: flow through the existing PRV and net available head.

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

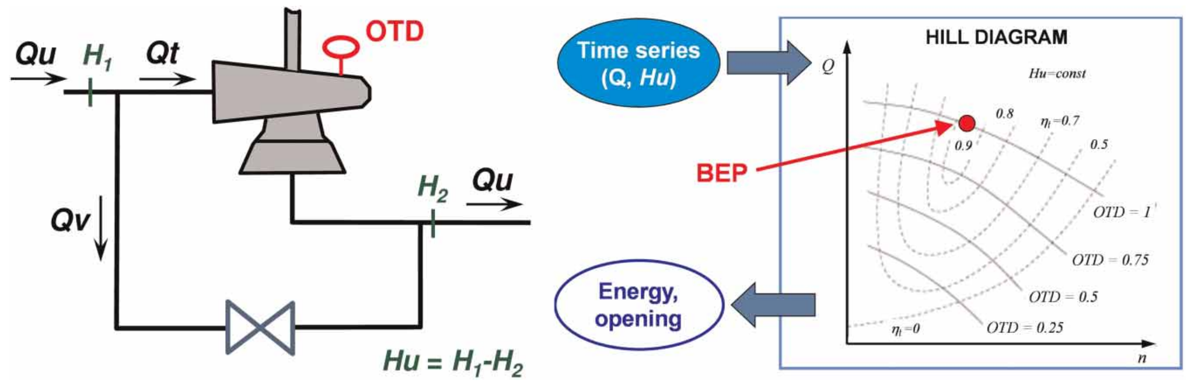

Figure 3 | Overall schematic of the turbine modelling tool.

The time series are simulated introducing a turbine, which is defined by a pair of values: flow (Q) and net available head (H) representing the best efficiency point (BEP) for that specific turbine. Therefore, each pair (Q; H) represents a single specific turbine, producing a certain amount of energy, when working under the flow-head conditions defined by the time series. Assigning a produced energy value (Z) to each pair (X, Y), the energy retrievable by different turbines with different BEP can be represented by a 3D surface (Figure 4).

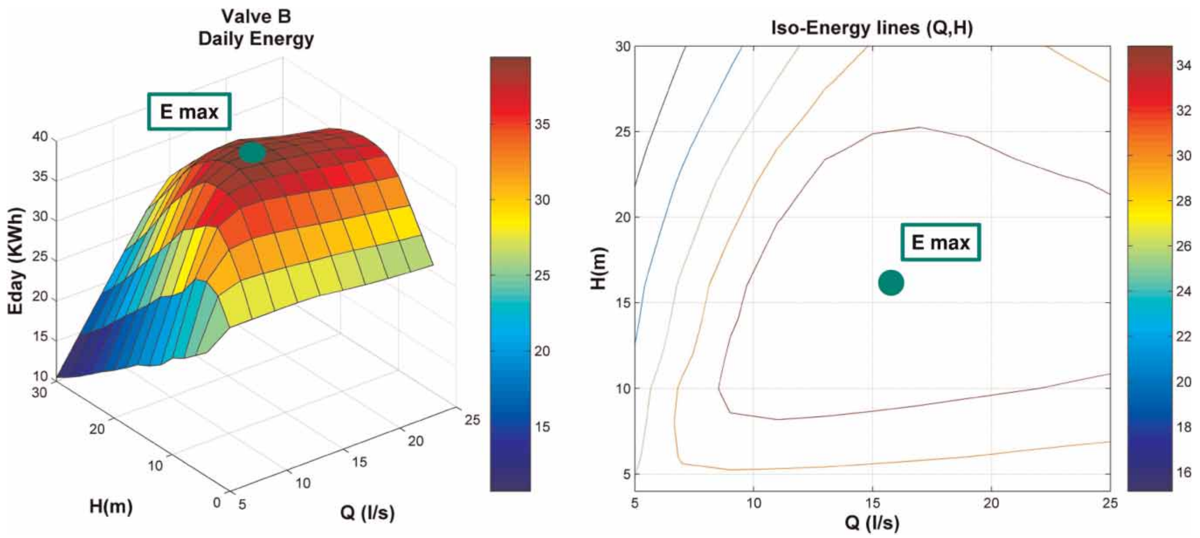

Figure 4 | 3D charts representing the daily energy production for turbines with different BEPs.

Case study Langhirano

The WSS of Langhirano (province of Parma, Italy) is a completely independent system, with a total pipeline length of 222 km, serving a population of about 10,000 inhabitants, on a surface of 70.8 km^2. The system retrieves water mostly from wells in the lower zones of the municipal area and occasionally from springs in the higher zones.

The most densely populated part of the system has been organised in seven DMAs, whose inlets are controlled by fixed setting PRVs. The current status of PRVs is shown in Table 3, where the setting is the pressure to be maintained in the downstream node.

To assess the effects of pressure management strategies a numerical model of the network has been implemented, making use of the water distribution system modelling software EPANET. The model

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

Table 3 | Energy produced by microturbines at each PRV

Valve (District)	Day 78 – PRV current setting (m)	Day 78 – turbine Egener [kWh] imposing the PRV current setting	Day 78 – PRV alternative setting (m)	Day 78 – turbine Egener [kWh] imposing the PRV alternative setting	% increase
B	35	38	20	70	+84.2
E	60	17	35	17	0.0
C	55	24	25	27	+12.5
D	30	12	16	17	+41.7
A	15	14.5	16	17	+17.2
F	35	160	22	180	+12.5
Total		265.5		328	+23.5

includes nearly 1,000 pipes as well as all pumps and valves for which the water utility has provided characteristics and efficiency curves. The model has been calibrated with a timestep of 5 minutes, on the basis of the available measured data, especially focussing on the possible position and magnitude of leakages. Four calibration days were considered, representative of two different working days and two non-working days.

Main results

First, alternative PRV settings were applied. The pressure settings at the valves have been modified, however still ensuring the minimum pressure required (5 m above the roof of each building). This resulted for calibration day 78 (working day) in a reduction of energy consumed from 2,356 to 2,189 kWh/d while the leakage rate was reduced from 31.1 to 24.8%.

Second, in order to achieve further energy savings, the on-off settings of the pumps have been slightly modified. The aim has been to make the plants work mainly during the off-peak hours, however still fulfilling the level of service required. These simulations were carried out assuming the alternative PRV settings. The system appeared somehow constrained, therefore relevant changes where not possible: 2,082 kWh energy consumed and 25.4% leakage rate.

Third, micro-generation simulation was done. The turbine modelling tool has been applied to all four present state scenarios (four different calibration days) and to the optimised alternative scenarios, adopting a Francis turbine with $n = 1{,}550$. Results of micro-generated energy in the PRV alternative condition are summarised in Table 3 and compared to the energy retrievable in the present state. The extension of the analysis to the alternative operating scenario 'PRV + pumps settings' has led to similar results in terms of energy produced.

For the sake of clarity, a summarising table is presented, introducing all the analized scenarios, both in terms of present state conditions and of alternative settings proposed. The daily micro-generated energy is compared to the daily energy consumed by the system pumps. Water leakage rate is reported as well (Table 4).

Conclusion on numerical dynamic tool

The analysis exhibits several results, which lead to different interesting considerations.

Although the amount of energy produced does not allow for the complete self-sustaining of the existing plants, it might however supply energy to auxiliary devices or service buildings used by the water utility. It should be noted that, larger networks are in general able to offer higher hydraulic heads and flows, which could lead to increased amounts of energy produced, compared to that consumed. This is mostly true for systems fed also by gravity and not just through pumps (such as Langhirano).

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

Table 4 | Summary of energy consumed, produced and leakage rate for each scenario

Scenario	Econs [kWh/d]	Egener [kWh/d]	%Gen/Cons	% Leakage
Day 66	2,582	256	9.9	27.7
Day 78	2,356	265	11.2	31.1
Day 80	2,388	267	11.2	29.6
Day 82	2,253	260	11.5	31.0
Optim PRV	2,189	328	15.0	24.8
Optim PRV + Pump	2,083	326	15.7	25.4

The inclusion of micro- turbines and their theoretical producibility is not in contrast with the measures taken to save water and energy (further pressure reduction and optimisation of pumps operation).

During the whole analysis, the DOTS tool proved to be both effective and flexible. The tool has a major advantage: it is capable of estimating the energy retrievable under certain dynamic conditions (namely flow and pressure time series), considering not just one single turbine, but a complete family of turbines sharing the same rotation speed number. This is particularly useful for the water utility management, as they will be able to perform cost-benefit analysis among the different turbines (especially considering those already available or not in the market) and the energy produced.

All in all, although the absolute value of energy produced by the turbines appear small when compared to the amount spent for the operation of the pumps, the insertion of the turbine/PAT is in general feasible and not in contrast to other interventions aimed to the improvement of water and energy management of the system.

UWOT TO ESTIMATE HYDRO ENERGY PRODUCTION IN WSS

This case study mainly focuses on hydropower generation along the external aqueduct network of the Athens WSS up to the four WTP supplying the city of Athens. The specific analysis requires a combined assessment of both water and energy in the urban water cycle and for this purpose the Urban Water Optioneering Tool (UWOT) was selected, which provides an appropriate modelling platform to facilitate this integrated approach. The analysis finally proposes a possible water-energy roadmap for the water supply system of the Greater Athens Area.

The UWOT

UWOT is a detailed bottom-up model that can simulate the entire urban water cycle from source to tap and then to disposal. UWOT follows a demand oriented approach and simulates the urban water cycle by aggregating and transmitting demand signals towards the source, instead of adopting a hydraulic conceptualisation and simulating water and wastewater flows (Rozos *et al.* 2010; Rozos & Makropoulos 2013). This approach has the advantage that the analysis is focussing on water users, allowing for the simulation of different type of households, user behaviour patterns, water technologies and appliances from more centralised to more decentralised options. In UWOT both demand and supply side measures and interventions can be investigated.

For the purposes of the specific analysis focussing on the water-energy nexus, energy related calculations in UWOT were further developed as described by Baki & Makropoulos (2014). Specifically, hydropower production calculations in the urban water cycle have been refined by taking into account the effect of variations in discharge and upstream reservoir water level. Power-discharge-water level (P-Q-H) curves can now be inserted in UWOT, instead of just using a constant specific

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

energy value in the hydro turbine model component. This allows for a more accurate estimation of the hydropower potential of the urban water system and more reliable assessment of related interventions, but at the same time offers the required flexibility according to the available information and required level of detail in each application.

Case study Athens

This approach and methodology was applied in the complex urban water system of Athens that serves approximately 4,300,000 people. Athens is located in Eastern Greece, a water scarce area, and the imbalance between water demand and water availability has resulted in the development of a very long water conveyance system transporting water from over 200 km away, from the western part of the country that receives most of the rainfall. Water demand in Athens after having increased rapidly over the recent decades has now stabilised at approximately 415 hm3 and the WSS is operating very close to its capacity (Efstratiadis *et al.* 2009).

Most of the water for supplying Athens comes from surface water sources and specifically from the primary reservoir system of Evinos and Mornos, from which water is transferred with gravity via the southern aqueduct branch. Various energy dissipation works along the southern aqueduct branch have been converted during recent years into hydropower plants (HPP) and at the moment six of them are in operation (generating 20.6 GWh/y). The available renewable energy potential can be further exploited with additional HPPs. The operation of the WSS is quite complex and challenging as there is a constant trade-off between WSS reliability and energy costs (Makropoulos *et al.* 2010).

Main results

The model of the Athens external water supply system was setup in UWOT employing various model components and brands, as well as making various assumptions and some simplifications necessary due to the complexity of the system. Initially, the schematisation of the current WSS was developed and P-Q-H curves were constructed and inserted in the model for all existing HPPs along the aqueduct system. The baseline scenario was run for eight hydrological years using historical time series for water demand and reservoir inflows. The model was calibrated both in terms of water and energy balances as described in Baki & Makropoulos (2014). The calibration exercise intends to capture current WSS operational decisions applied by the water company and actually confirms that the current operational policy aims at reducing energy costs by minimising water abstractions from energy intensive sources.

Various energy related interventions with a particular focus on hydropower production were then identified in close collaboration with the Athens water company. These interventions were grouped into different phases according to their estimated implementation timeframes. The identified groups of interventions referring to the Athens external water supply system are presented in Table 5.

Table 5 | Identified energy related interventions of the Athens external water supply system

	Step 1: immediate	Step 2: short-term	Step 3: medium term	Step 4: long term
Proposed interventions	• Pump replacement (Kiourka) • Operational improvement of existing HPPs • New HPP Klidi	• New HPP Helidonou	• New HPP Giona (2nd unit)	• New HPP Outlet of Evinos–Mornos tunnel

For each of the different intervention phases separate UWOT schematisations and models were developed, which were run using current water demand levels and 100-year synthetic timeseries for the hydrologic inputs. The future scenarios models were also run with different WSS operational

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

rules corresponding to different WSS reliability levels. Model results were evaluated using selected indicators, the renewable energy fraction and energy intensity, i.e. the amount of energy required per unit volume delivered. Figure 5 shows the potential evolution of the total and net energy intensity, the latter is estimated after taking into account hydropower generation, of the external water supply system through the different implementation phases, constructing thus a potential water-energy roadmap for the Athens WSS.

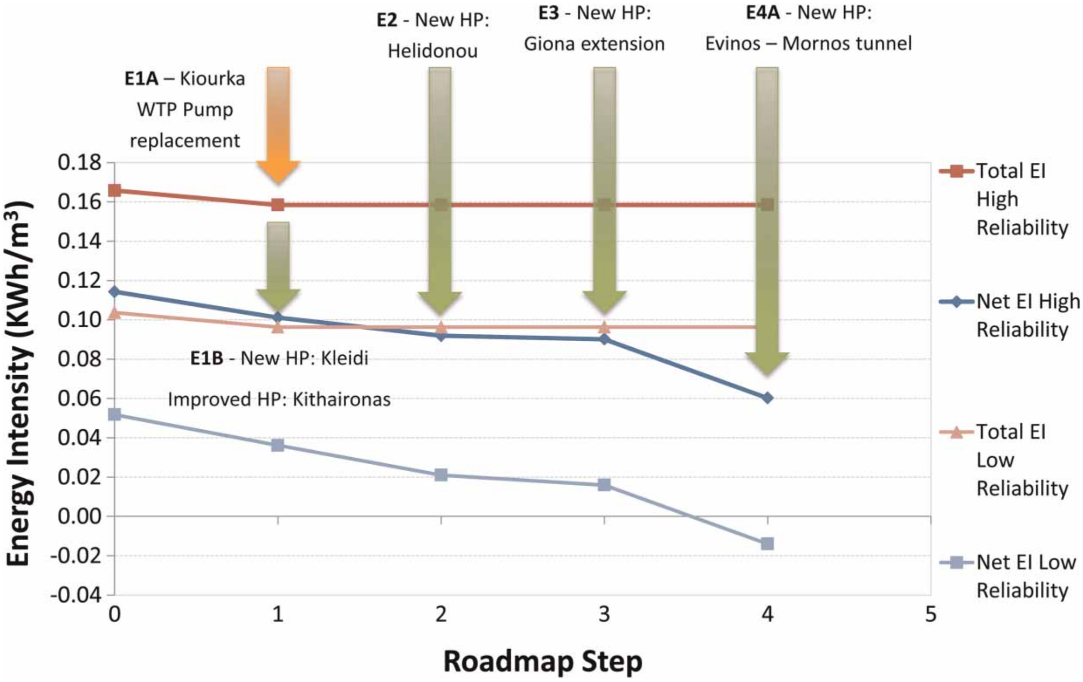

Figure 5 | Evolution of energy intensity (net and total) for the proposed water-energy roadmap.

Conclusion on UWOT

The results of the analysis suggest that there is a substantial energy recovery potential through hydropower generation along the external aqueduct network of the Athens urban water system and the implementation of the proposed water-energy roadmap could lead to a considerable reduction of the system's energy footprint. The more short-term interventions could have a considerable impact on net energy consumption without having too many technical complications or requiring too many resources for their implementation. The results of the work indicate that the most promising intervention in terms of hydropower production is the development of the hydropower plant at the exit of the Evinos–Mornos tunnel due to the substantial volume of water transferred annually between the two reservoirs. However, the specific project is technically challenging and requires a detailed technical analysis and financial feasibility study. It should also be noted that socio-economic uncertainties and legislative and bureaucratic processes currently in place could create barriers and delays in the implementation of renewable energy projects. Finally, the current analysis highlights the importance of the WSS operation, which plays a very important role in the water-energy nexus of the urban water system, but also the fact that there should also be a careful consideration of the trade-off between system reliability and energy costs.

The models developed in UWOT showed an overall good performance and the baseline model adequately simulated the current state of the water-energy nexus in the Athens external aqueduct system. It is considered that the model can accurately estimate hydropower production and assess the effect of

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

related projects, after having expanded its capabilities (Baki & Makropoulos 2014). More generally, since UWOT can capture water-energy interactions in the entire urban water cycle, it is suggested that UWOT can provide a common platform for the combined analysis of water and energy. The effect of energy related interventions on the energy footprint of WSS can be estimated through this tool and methodology, as well as the effect on the WSS's reliability which is crucial for the services provided by the water utility.

CONCLUSIONS

There is significant potential for energy recovery through the use of micro-hydropower installations in WSS. In 4 case studies, multi-objective management tools have been used to optimise the hydro energy potential in WSS, and simultaneously optimise the hydraulic and energy efficiency. From the case studies can be concluded, that:

- Performing an energy audit of pressurised water networks, gives a good indication of the energy problems and possibilities and locations for energy saving. In the case of Alcoy, the energy audit revealed that Erl represent 19% of the total energy supplied. Introducing a PAT could result in an energy recovery of 631 kWh/d.
- In the Algarve, after having applied an energy audit, two multi-criteria decision-making methods resulted in the selection of the preferred energy-efficient operating water supply scheme, i.e. the year round operation of Beliche WTP with energy recovery by a micro-hydropower plant with two PATs.
- Numerical dynamic modelling results of turbines in the Langhirano water distribution network shows that the inclusion of microturbines matches with the measures taken to save water and energy, i.e. further pressure reduction and optimisation of pumps operation.
- In Athens, the UWOT can accurately estimate the hydro energy potential of the urban water system. The development of an additional hydropower plant at the outlet of Evinos–Mornos tunnel appeared to have the biggest impact on net energy consumption and renewable energy fraction.

The presented methods showed that through an integrated approach the WSS can be optimised for both hydraulic and energy efficiency. By applying multi-objective management tools, the full potential of hydro energy can be exploited in balance with the optimal hydraulic performance and water supply service.

ACKNOWLEDGEMENTS

The research results presented have been executed within the framework of the TRUST project: Transitions to the Urban Water Services of Tomorrow. The TRUST project has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 265122.

REFERENCES

Araujo, L. S., Ramos, H. & Coelho, S. T. 2006 Pressure control for leakage minimisation in water distribution systems management. *Water Resource Management* **20** (1), 133–149.

Awad, H., Kapelan, Z. & Savic, D. A. 2010 Optimal setting of time-modulated pressure reducing valves in water distribution networks using genetic algorithms. In: *Proceedings of the 10th International on Computing and Control for the Water Industry, CCWI 2009*, pp. 31–37, CRS Press, Sheffield, UK.

Baki, S. & Makropoulos, C. 2014 Tools for Energy Footprint Assessment in Urban Water Systems. In: *Water Distribution Systems Analysis Conference*, *14–17* July 2014, Bari, Italy.

Water Practice & Technology Vol 10 No 2
doi: 10.2166/wpt.2015.024

Basupi, I., Kapelan, Z. & Butler, D. 2014 Reducing life-cycle carbon footprint in the (re)design of water distribution systems using water demand management interventions. *Urban Water Journal* **11** (2), 91–107.

Cabrera, E., Pardo, M. A., Cobacho, R. & Cabrera Jr., E. 2010 Energy audit of water networks. *Journal of Water Resource Planning & Management* **136** (6), 669–678.

Cabrera, E., Gómez, E., Cabrera Jr., E., Soriano, J. & Espert, V. 2014 Energy assessment of pressurized water systems. *Journal of Water Resources Planning & Management* (accepted). DOI: 10.1061/(ASCE)WR.1943-5452.0000494.

Carravetta, A., Fecarotta, O., Del Giudice, G. & Ramos, H. M. 2012 Energy production in water distribution networks: a PAT design strategy. *Water Resources Management* **26**, 3947–3959.

Dias, J. Almeida, Figueira, J. R. & Roy, B. 2006 *The Software ELECTRE III-IV: Methodology and User Manual (Version 3.x)*. LAMSADE, University Paris-Dauphine, Paris, France.

Efstratiadis, A., Karavokiros, G. & Mamassis, N. 2009 *Master Plan of the Athens Water Resource System - Year 2009, Maintenance, Upgrading and Extension of the Decision Support System for the Management of the Athens Water Resource System*. National Technical University of Athens, Athens.

Figueira, J., Greco, S. & Ehrogott, M. 2005 *Multiple Criteria Decision Analysis: State of the Art Surveys*. Springer, Inc., New York, USA.

Frijns, J. (ed.) 2014 Intervention concepts for energy saving, recovery and generation from the urban water system, Report D45.1. TRUST project.

Frijns, J., Middleton, R., Uijterlinde, C. & Wheale, G. 2012 Energy efficiency in the European water industry: learning from best practices. *Journal of Water and Climate Change* **3** (1), 11–17.

Frijns, J., Hofman, J. & Nederlof, M. 2013 The potential of (waste)water as energy carrier. *Energy Conversion & Management* **65** (1), 357–363.

Gonçalves, F. V., Costa, L. H. & Ramos, H. M. 2012 Best economical hybrid energy solution: model development and case study of a WDS in Portugal. *Energy Policy* **39** (6), 3361–3369.

Lenzi, C., Bragalli, C., Bolognesi, A. & Artina, S. 2013 From energy balance to energy efficiency indicators including water losses. *Water Science and Technology: Water Supply* **13** (4), 889–895.

Makropoulos, C., Efstratiadis, A. & Koukouvinos, A. 2010 *Appraisal of Financial Cost and Proposals for a Rational Management of the Hydrosystem, Untreated Water Costing for the Water Supply of Athens*. National Technical University of Athens, Athens, Greece.

McNabola, A., Coughlan, P., Corcoran, L., Power, C., Williams, A. P., Harris, I., Gallagher, J. & Styles, D. 2013 Energy recovery in the water industry using micro-hydropower: an opportunity to improve sustainability. *Water Policy* **16** (1), 168–183.

Ramos, J. S. & Ramos, H. M. 2009 Sustainable application of renewable sources in water pumping systems: optimized energy system configuration. *Energy Policy* **37** (2), 633–643.

Ramos, J. S. & Ramos, H. M. 2010 Multi-criterion optimization of energy management in drinking systems. *Water Science & Technology: Water Supply* **10** (2), 129–144.

Ramos, H. M., Kenov, K. N. & Vieira, F. 2011 Environmentally friendly hybrid solutions to improve the energy and hydraulic efficiency in water supply systems. *Energy for Sustainable Development* **15** (4), 436–442.

Rogers, M. & Bruen, M. 2000 Using ELECTRE III to choose route for Dublin Port Motorway. *Journal of Transportation Engineering* **126** (4), 313–323.

Rozos, E. & Makropoulos, C. 2013 Source to tap urban water cycle modelling. *Environmental Modelling and Software* **41**, 139–150.

Rozos, E., Makropoulos, C. & Butler, D. 2010 Design robustness of local water-recycling schemes. *Journal of Water Resources Planning & Management* **136** (5), 531–538.

San Cristóbal Mateo, J. R. 2012 *Multi criteria Analysis in the Renewable Energy Industry*. Springer, Berlin-Heidelberg, Germany.

Souza, E. V., Covas, D. I. C. & Soares, A. K. 2011 Novel standardized energy auditing scheme in water supply systems. In *11th International Conference on Computing and Control for the Water Industry, 5-7 September*, Exeter, UK.

Tzeng, G. H. & Huang, J. J. 2011 *Multiple Attribute Decision Making: Methods and Applications*. Taylor & Francis Group, Boca Raton, USA.

Vilanova, M. R. N. & Balestieri, J. A. P. 2014a Energy and hydraulic efficiency in conventional water supply systems. *Renewable and Sustainable Energy Reviews* **30** (10), 701–714.

Vilanova, M. R. N. & Balestieri, J. A. P. 2014b Hydropower recovery in water supply systems: models and case study. *Energy Conversion and Management* **84**, 414–426.