Impact Assessment of Household Demand Saving Technologies on System Water and Energy Use

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Case Study

ABSTRACT

Climate change, population growth, migration, urbanisation, and ageing infrastructure will all impose significant strains on the urban water services in Europe, and cities across Europe will experience increasingly frequent shortfalls in supply/demand balance. It is widely accepted that the mitigation of these and other emerging challenges should be sensitive to increasing energy prices, the environment, and the desire for low carbon intensity solutions. This paper presents the development of a new methodology for assessing the impact of household water savings from different water demand management interventions based on their water-related energy use and cost, as well as their impact on the supply/demand balance. The methodology has been applied to the water distribution system of a European city to demonstrate its application using different water demand management interventions for different types of water savings. Sensitivity analysis for different population growth rates that are representative of the different growth rates across the EU was carried out. The results show different degrees of water, energy, and cost savings can be achieved depending on the type (s) and proportion of household micro-component appliances and fittings considered. In all the intervention strategies considered, there are important trade-offs to be made between the different performance indicators as not all interventions will result in water savings and/or reductions in water-related energy use and costs or have a positive impact on supply/demand balance.

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1. INTRODUCTION

The quality and the quantity of fresh water resources are increasingly facing challenges in many parts of the world as a result of climate change, population growth, migration, urbanisation, and ageing infrastructure. In the EU, environmental regulations and national legislations are also forcing Water Service Providers (WSP) to comply with increasingly stringent limits on chemical contaminants in drinking water, which further reduces the potential sources of supply [1,2]. Seasonal or inter-annual variations in the availability of water also lead to water stress [3].

However, despite these challenges the underlying trend is that the demand for water is increasing [4]. If the current population and demand trends persist, there will be an increase in global water demand of about 64 billion cubic metres per year [5]. It is estimated this demand will surpass availability by 56% by 2025, and it is likely that water resource development will not keep up with population growth [6]. In order to sustainably meet future water demand, various types of interventions need to be taken into consideration.

Historically, efforts to satisfy demand of water have often been expended principally on increasing the supply of resources, which were available abundantly and at relatively low cost [7,8]. However, supply augmentation such as the development of new reservoirs, dams, treatment plants, desalination plants and large scale water-transfer infrastructures are costly, and the over reliance on the development of new supply systems to respond to increasing demand often encounters public opposition as they are viewed as a potential cause of environmental degradation. Supply augmentation also tend to be unresponsive to economic, environmental, social, and political constraints and the important contributions to supply that can be obtained from comprehensive demand interventions [1].

However, in the face of growing demand, current uncertainties, and change; reducing the specific demand for water is the best source of 'new' water [9]. Water Demand Management (WDM) aims to sustainably reduce water use to conserve the resource, save water, and reduce negative environmental impacts whilst still satisfying the needs of consumers. WDM interventions can also provide energy and cost savings have a positive impact on supply/demand balance, extend the life of existing Water Distribution Systems (WDS), and reduce the total volume of wastewater arriving at treatment works.

The water industry is energy intensive and on average between 2-3% of the world's energy use is used to treat water to potable quality, deliver it to consumers, and to process and dispose of wastewater [10]. In the UK for example, energy use in the water industry rose 10% between 2001 and 2011 to 9, 016 GWh [11]. However, this represents only 11% of the total water-related energy use, with 89% attributed to domestic water use, particularly hot water use which constitutes 95% of household water-related energy use [12]. Water supply and wastewater management operations alone is therefore a poor indicator of the energy use associated with the urban water sector [12] and an assessment of household water-related energy use is needed to better determine energy use in the urban water sector.

Most of the urban water use in the EU is for household water use [13] to satisfy basic needs for drinking water and sanitation and other needs such as house cleaning, dishwashing, clothes washing, and landscaping [14]. The amount of water use in households depends on

a wide range of factors, including household occupancy, type, income, and water prices [14]. This amount is increasing as a result of increasing use of water using appliances due to increasing standards of living and personal hygiene [13]. One way of reducing household demand is to make existing homes more water efficient [15], which could be accomplished by using efficient household micro-component appliances and fittings, such as lower flush WCs, lower flow showers and taps, and efficient white goods [16].

As household water and energy use are inextricably linked, reducing household water use and using efficient household appliances and fittings, especially hot water using appliances can also significantly reduce overall energy demand and household energy cost [12,17]. On average, around a third of household energy use is for heating and hot water use. Also, because the level of water-related energy use has a direct relationship with GHG emissions, WDM interventions can be viewed not only as a potential means of aiding the security of future water supplies but also as a means of reducing emissions [12].

However, not all WDM interventions will result in reduction in water-related energy use and some interventions could increase energy use. For example, reducing mains water use with rainwater may result in increasing water-related energy use as a result of energy required to pump rainwater. In general, if water use is to be reduced then some other factor must change to accommodate this, and where a reduction of water use or water-related energy use result in an increase of the other, it is not necessarily clear which is the most sustainable outcome [18]. An understanding of these water-energy-cost savings trade-offs is therefore essential in order to plan for sustainable WDM interventions.

Several methodologies have been developed for assessment of WDM interventions, including AQUACYCLE [19], UWOT [20], CWB [21] and UVQ [22]. These are all based on water balance modelling which assess the performance of integrated urban water supply, demand, and wastewater systems. Other methods that assess the performance of household water and energy use such as the Code of Sustainable Homes [23] and the Sustainable Building Alliance [24] do so in isolation of each other and provide no means of assessing the inevitable trade-offs that could result between different performance indicators. These methods also do not consider water-related energy use as a component of the performance of either energy or cost savings and cannot be used to assess the extent to which household water savings can fully affect energy use.

This paper presents a new methodology for the impact assessment of household water savings from different WDM intervention strategies based on their water-related energy use, cost and their impact on the supply/demand balance of a WDS. The methodology uses 2006 average EU per capita water use data and household micro-component water use breakdown, as well as assumptions from previous work. The methodology differs from previous methodologies in terms of understanding the impact of household water savings on water-related energy use and cost and the resulting water-energy-cost savings trade-offs that can arise from different types of household WDM intervention strategies.

2. METHODOLOGY

The methodology uses the 2006 average EU water use of 150 Litres/Capita. Day (LCD) [25,26] and household micro-component water use breakdown as a baseline for the impact assessment (Table 1). Although average figures mask variations of water use across countries, regions and even within communities and over time [3,1], they provide a basis for comparing the baseline impacts of WDM interventions on different performance indicators [7]

where case study data is not fully or readily available. Moreover, the per capita figures used in the methodology are based on 2006 figures, the last accurate EU average figures we could find. This may have changed over time, especially given the recent near-drought conditions experienced in some parts of Europe.

Table 1. Average 2006 EU household micro-component water use, % [26]

Household micro-components	Water use, %
WC	35
Bath	15
Shower	5
Washbasin tap	8
Kitchen sink tap	25
Outdoor tap	6
Washing machine	12
Dishwater	4
TOTAL	150

2.1 Water Demand Management Options

Different types and combinations of household micro-component appliances and fittings can be used to reduce water use, as well as provide savings in household water-related energy use, costs, and have an impact on supply/demand balance of WDS. The WDM options considered in the methodology include different types of household micro-component appliances and fittings, domestic Grey Water Recycling (GWR) and Rainwater Harvesting (RWH) systems (Table 2). In the baseline scenario in the methodology, it is assumed that 100% of household water use is from mains water supply – i.e. no GWR and RWH systems are in use. In the other scenarios, grey water from baths and showers can be used by GWR systems to flush WC's, and rainwater can be used by RWH systems for WC flushing, clothes washing, and outdoor use as household WDM interventions. Social impacts have not been considered due to lack of data on the social impact of WDM interventions.

Efficient household micro-component appliances and fittings can offer the potential for significant water savings at point of use and can potentially reduce water use from 150-80 LCD [27]. Retrofitting households and efficiently fitting new developments is considered the least sensitive WDM intervention to issues of human interface, as no lifestyle changes are required, and are therefore the easiest intervention to implement [26]. Some of these technologies can also have short payback periods which can further enhance their uptake possibilities [27]. Three types of efficient household appliances and fittings have been considered in the methodology (Table 2):

i) Conventional household appliances – these are the current household appliances, and have been assumed to represent 100% baseline household asset ownership.
ii) Water efficient household appliances – these are the current BATNEEC (Best Available Technologies not Entailing Excessive Costs) appliances and fittings – such as new WC's, taps, baths, showers and white goods.
iii) Retrofit devices and fittings for household appliances – these are a comparably low-cost alternative to replacing households with efficient appliances which provide a low-cost means of water, energy and costs savings. These include cistern displacement and interruptible flush devices for WCs and flow restrictors and aerators for taps.

Table 2. Types of household micro-component appliances and fittings

Household appliance and fitting	Type
WC - 10 litres/flush	Conventional
WC - 7.5 litres/flush	Efficient
WC - 6 litres/flush	Efficient
WC - 6/4 litres/flush	Efficient
WC - 6/3 litres/flush	Efficient
Cistern displacement device - HIPPO	Retrofit
Cistern displacement device - SAVE-A-FLUSH	Retrofit
Retrofit flush device	Retrofit
Bath	Conventional
Medium bath	Other conventional
Large bath	Other conventional
Gravity mixer shower	Conventional
Electric shower	Efficient
Power shower	Efficient
Retrofit shower head	Retrofit
Retrofit shower flow regulator	Retrofit
Wash basin tap	Conventional
Washbasin tap insert – aerator	Retrofit
Washbasin tap insert – flow regulator	Retrofit
Kitchen sink tap	Conventional
Kitchen sink tap – aerator	Retrofit
Kitchen sink tap – flow regulator	Retrofit
Outdoor tap	Conventional
Washing machine	Conventional
Efficient washing machine	Efficient
BATNEEC washing machine	Efficient
Dishwasher	Conventional
Efficient dishwasher	Efficient
Grey Water Recycling system	Efficient
Rainwater Harvesting system	Efficient

2.1.1 Household appliances and fittings

The baseline water use for each household micro-component appliance is based on the volume of water use and frequency of appliance use per person per day (Table 3). For showers, washbasin taps, kitchen sinks taps and outdoor taps, the volume of water use is based on event duration and appliance flow rate. The factors affecting the volume of water used for bathing are the type of bath, its capacity, and its usage pattern [28]. The mean life spans used are in line with current industry standards for household micro-component appliances and fittings [28]. Although ideally energy appliances should be modelled with increased efficiency over the long-term, all energy appliances considered have been assumed to have constant efficiency for the duration of the planning horizon as it is difficult to anticipate relevant technological developments and estimate how much more efficient appliances will become in the future and when.

Table 3. Baseline assumptions for household micro-component appliances water use [26,28]

Household micro-components	Volume of water/use, litres	Frequency of use/ day	Event duration, minutes	Flow rate, litres/ minutes	Water use, LCD	Lifespan, year	Asset ownership, %
WC – 10 litres/flush	10	5.25	n/a	n/a	52.5	15	100
Bath	80	0.28	n/a	n/a	22.4	15	100
Shower	15	0.5	n/a	n/a	7.5	12	100
Washbasin tap	6	2	0.7	9.2	12.0	15	100
Kitchen sink tap	10	2.25	0.7	15.4	22.5	25	100
Outdoor tap	9	1	n/a	n/a	9	n/a	100
Washing machine	100	0.18	n/a	n/a	18	13	100
Dishwasher	29	0.21	n/a	n/a	6.1	13	100
TOTAL					150		

2.1.2 Alternative water systems

Alternative systems such as GWR and RWH can limit the amount of mains water use for non-potable uses and water abstraction needs, as well as have a positive effect on wastewater by delaying/reducing peak inflow into wastewater system. Current domestic systems can be high value, low cost, and low energy use systems that can also be utilised to reduce water use by limiting the amount of mains water use for non-potable uses – such as WC flushing, clothes washing, and outdoor uses, thereby reducing household water use. If used for WC flushing for example, a well-designed and fully functional system could potentially save about a third of the mains water used in households. Further reductions can be made if used for non-potable uses such as clothes washing and outdoor use [29].

The domestic WDM systems considered are domestic GWR and RWH systems. The GWR system has been assumed to collect grey water from baths and showers, which then is treated and reused for WC flushing. The quantity of household water from washbasins, showers and baths is similar to that used for household WC flushing. This means supply of water for household WC flushing will roughly equate to demand, as each person will generate their own water. This will in turn result in minimal to no reliance of mains water top-up and smaller tank size. The RWH system collects rainwater which can be used for WC flushing, outdoor water use (garden watering, car washing), and washing machines, and can therefore potentially provide further water savings compared to GWR systems. RWH systems are heavily reliant on rainfall, and therefore when it does not rain for some time and water cannot be collected, the system will revert to mains water supply to top-up.

2.2 Performance Indicators

Three performance indicators have been used to assess the impact of water savings from different WDM intervention scenarios: (i) energy use; (ii) cost; and (iii) supply/demand balance.

2.2.1 Water-related energy use

All household appliances that use hot water have associated water-related energy use. This energy use depends on both the volume of water used, and the temperature difference between hot and cold water use [18,12]. The assumptions for household hot water use are provided in Table 4. This includes the temperature at which mains water is delivered to households, mean temperature at point of use, and the percentage split between hot and cold water mix at point of use for baths, showers, washbasin taps, and kitchen sink tap. Boiler efficiency refers to the amount of energy that is lost from the boiler [18]. For example, 80% efficiency means that 20% of the energy is lost. It has been assumed that all washing machines and dishwashers considered internally heat cold water.

Table 4. Household hot water assumptions [18]

Variable	Assumptions
Average temperature of mains water	9ºC
Shower temperature	41ºC
Bath water temperature	42ºC
Washbasin tap temperature	42ºC
Kitchen sink tap temperature	55ºC
Washbasin tap hot : cold water contribution to total volume	50:50 split
Kitchen sink hot : cold water contribution to total volume	50:50 split
Bath hot : cold water contribution to total volume	2 parts hot : 1 part cold
Shower hot : cold water contribution to total volume	2 parts hot : 1 part cold
Heating method	Electricity
Boiler efficiency	80%

Annualised household water-related energy use is calculated using the sum of energy used to produce hot water use, Q (KWh) (Equation 1) and the energy used for GWR and RWH, E (Equation 2).

$$Q = \frac{C_P \times m \times \Delta T}{c \times \eta_b}$$

.... (1)

where C_p is the specific heat capacity of water (J/kg/^{0}C), m is the mass of water (kg), ΔT is the change in temperature between mains water and water use temperature (^{0}C), the constant c is the conversion factor from Joules to KWh, and η_b is the boiler efficiency (MTP 2011a, Fidar et al 2010). The energy use for GWR and RWH pumping E is calculated using:

$$E = p \times \left(\frac{m}{60}\right) \times h \times d \times \varphi$$

.... (2)

where p is the number of times the system cycles in an hour, m is the duration of the cycle (minutes), h is the number of hours in a day, d is the number of days a month and φ is the running wattage of the GWR or RWH system (KWh).

2.2.2 Cost

The cost of an intervention, C (EUR/year), is based on annualised total cost over an intervention interval calculated using the sum of annualised CAPEX of an intervention over the lifetime of the household micro-component appliances and fittings over their life time (Equation 3) and the annual operational cost of the appliances and fittings (i.e. energy use for GWR and RWH pumping and treating systems and hot water production).

$$C = K_0 \times \frac{r(1+r)^n}{(1+r)^{n-1}} \times W$$

.... (3)

where K_0 is the CAPEX at the beginning of the intervention interval (EUR), r is the discount rate (%), n is the life span of the appliances and fittings (yearsand W is the proportion of households in the WDS with the micro-component appliances and fittings (%). It is assumed that the total cost of interventions is borne at the beginning of an intervention. However, CAPEX has been annualised because of the different life spans of the appliances and fittings.

2.2.3 Supply/demand balance

The supply/demand balance is calculated indirectly in terms of headroom, H (ML/year), available between supply (S) and demand (D) (Equation 4). Negative headroom indicates supply/demand deficit.

$$H = S - D$$

.... (4)

3. CASE STUDY

The methodology has been applied to a case study of the WDS of a European city by running different WDM interventions. The aim was to assess the impact of water savings from the different WDM intervention strategies (i.e. different types and combinations of WDM options) based on their energy use, cost and impact on supply/demand balance of the WDS.

3.1 Case Study Description

The case study is of a water supplier which is operating on a 25 year concession contract that began in 2000. The WDS consists of 3 treatment plants, 8 pumping stations and 2, 400 km of water pipes and sewerage pipes each. Since privatisation, the water supplier has invested 20 million EUR and has seen significant improvement at all system levels: Non Revenue Water (NRW) has decreased from 300-90 million m^3 per year and water use has decreased from 400-150 LCD, perhaps as a result of universal metering coverage and the higher water rates. A summary of existing household conditions in the WDS is given in Table 5. Assumptions in Table 6 have been used where case study data is not available.

Table 5. Existing household conditions in the WDS

	Data
Permanent population	1, 900, 000
Maximum supply capacity, m^3/day	1, 600, 000
Total system supply capacity, m^3/year	520, 000, 000
Total domestic water demand, m^3/year	225, 000, 000
Total household demand m^3/year	102, 000, 000
Water rate, EUR/m^3	0.8
Total embodied energy (electricity), kWh/year	38, 000, 000
Domestic embodied energy, kWh/year	23, 000, 000
No of domestic metered connections	108, 000
Domestic metering coverage, %	100

Table 6. Household assumptions in the WDS

Assumption	Data
Average household size, people	2.5
No of households	760, 000
Population growth rate, %	-0.2
Unit cost of energy, EUR/kWh	0.12
Discount rate, %	0.02
Interest rate , %	0.04

The water supplier has 100, 000 contractual customers, serving a population of 1.9 million. With no major industrial use, water use in the city is mainly domestic. The current total water demand is around 225 million m^3 per year, about 45% (102 million m^3 per year) of which is for domestic use and about 40% (90 million m^3 per year) of which is NRW. The remaining 15% is for commercial and municipal water use. The NRW of 40% represents losses only to point of metering, as the water supplier's responsibilities are limited to point of customer metering. In terms of supply/demand balance, the water supplier has the capacity to produce around 520 million m^3 per year, of which only about 225 million m^3 per year is sold. Therefore the water supplier is currently producing is twice as much water as it sells.

Despite the huge water savings made since privatisation, water use can be further reduced by using WDM interventions, which can also lead to reduction in energy use and cost, as well as have an impact on supply/demand balance which could improve the security of future water supply without corresponding investment in supply infrastructure. However, despite universal metering of domestic use in the WDS, around 1,000 of the water supplier's connections are to housing blocks serving up 1,000 inhabitants each. These connections represent around 80% of domestic water use and access to them is only through household associations. There is therefore currently no data available for per capita or household micro-component breakdown and as such, assumptions based on average EU water use and household micro-component breakdown, as well as other assumptions from previous work have been used.

3.2 Case Study Assumptions

Assumptions have been made about average household data, such as the household occupancy, household size, and the number of households (Table 6). These are assumed to

remain constant over the planning horizon (2010–2050). The figures for population growth rate (PGR) and the unit cost of energy have been obtained from World Bank and Europe's Energy Portal respectively [30,31]. It is assumed that the negative population growth in Table 6 will remain constant over the planning horizon. Assumption for interest rate is based on the European Central Bank's long-term interest rate for EU Member States [32].

3.3 Intervention Scenarios

Different degrees of water savings can be achieved depending on the WDM intervention scenario considered, and impacts of water saving on water-related energy use, cost and on supply/demand balance can vary significantly. Three different scenarios have been considered on the case study WDS to assess the impacts of different water savings in terms of their energy use, cost and supply/demand balance. All the scenarios considered in the case study assume the current negative PGR remains the same over the planning horizon:

i)   Business as usual (BAU) scenario – where the current EU average per capita water of 150 LCD remains the same, with household micro-component appliances and fittings in line with average product lifespan.
ii) Alternative systems (ALT) scenario – where household micro-component appliances and fittings are replaced in line with average product lifespan, and GWR and RWH systems are introduced at 5% of households at each intervention interval, which will result in overall reduction of volumetric water use.
iii) Aggressive (AGG) scenario – where water use is reduced by 30 LCD, which will result in water use of 120 LCD by 2050. For example, a reduction of per capita water use to 120 LCD at 2050 by reducing water use by 10 LCD between 2012–2020, 2020–2030 and 2030–2040 by using different combinations of household appliances and fittings and GWR and RWH systems.

3.4 Results and Discussion

In the BAU scenario, there is a decrease in per capita water use by 9 LCD to 141 LCD at the end of the planning horizon (2050), which decreases overall water demand from 104 ML/yr to 83 ML/yr (Fig. 1). Headroom increases as a result of both the reduced per capita water use that will arise from the negative PGR and replacement of appliances and fittings; indicating no water resource stress issues even without increase in supply infrastructure or dedicated WDM strategy due to headroom as shown in Fig. 1. The result also shows a decrease in total household water-related energy use and costs, even with the CAPEX for the micro-component appliance and fitting replacement in line with average product life spans. The proportion of household micro-component water use also changes in the BAU intervention given the types and proportion of the appliances and fittings used over time. Less water is used for WC flushing, washing machines and dishwashers as a result of the type (s) and proportions of micro-component appliances and fittings considered (Table 7).
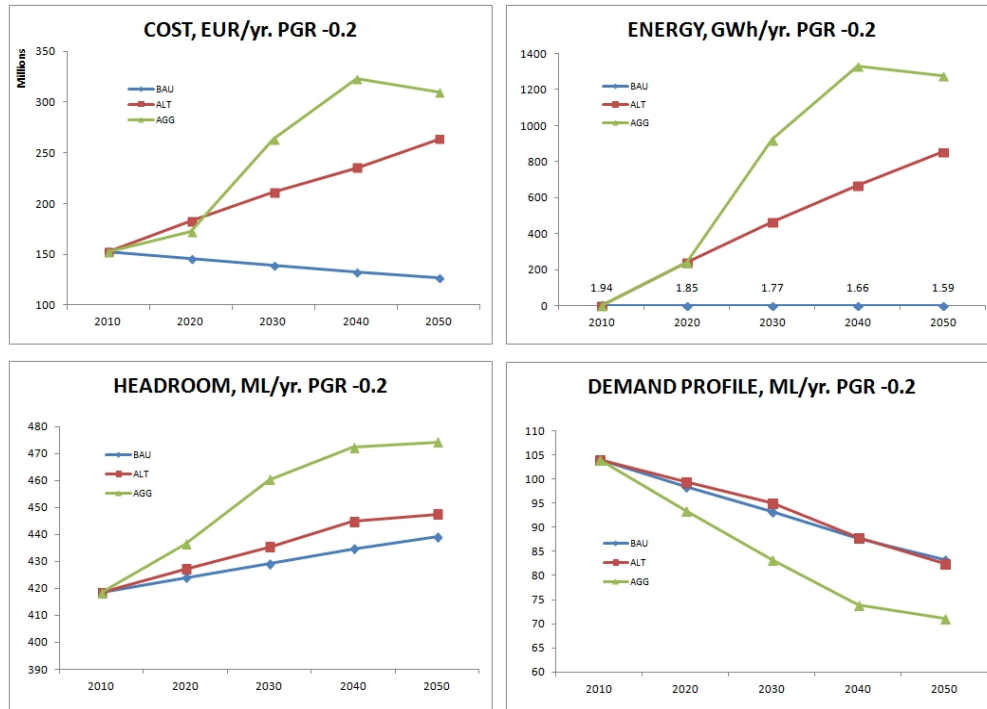
Fig. 1. Results for the three WDM intervention strategies under current negative PGR

Table 7. Household micro-component water use at the end of the planning horizon (2050)

Household micro-components	Baseline, LCD	BAU, LCD	ALT, LCD	AGG, LCD
WC	35	28	29	25
Bath	15	25	25	15
Shower	5	6	6	8
Washbasin tap	8	8	8	9
Kitchen sink tap	15	15	15	18
Outdoor tap	6	6	6	8
Washing machine	12	9	8	10
Dishwasher	4	3	3	3

In the ALT scenario, the result shows an overall reduction in volumetric mains water use and an increase in costs and headroom, with a substantial increase in energy use given the introduction of GWR and RWH systems at 5% of households at each interval (Fig. 1). Energy use significantly increases in this scenario given the energy use of GWR and RWH systems even with improved energy use of current GWR and RWH systems. The proportion of water use by source changes over time given the introduction of GWR and RWH systems, as this reduces the per capita mains water use by 10 LCD, a litre more than in the BAU scenario. However, this scenario will cost significantly more than BAU given both the CAPEX required for GWR and RWH systems and the cost of additional energy use for pumping grey water and rainwater. The proportion of micro-components water use also changes over time given the different appliances and fittings that will be used over time (Table 7). As with the

BAU scenario, less water is used for WC flushing and white goods. Water use for taps remains the same whilst that for baths and showers increases.

In the AGG scenario, there is a reduction in per capita by 30 LCD to 120 LCD at the end of the planning horizon (Fig. 1). The cost of this scenario is significantly higher than that of the ALT scenario because of the types and proportion of household micro-component appliances and fittings considered. The proportion of water use by source also changes over time given the introduction of GWR and RWH systems, as this reduces the amount of volumetric mains water use. The proportion of household micro-components water use also changes over time given the proportion and types of household micro-component appliances and fittings that will be used over time (Table 7).

Overall, the BAU scenario performs the best in terms of energy use and cost, and performs the worst in terms of headroom. This could become an issue if the current situation changes, for example if demand increases from an increase in population or industrial water use, or if supply is affected by climate change without a corresponding increase in supply resources. However, a reduction in demand will result in less revenue for WSPs and the unit cost of water may have to increase to reflect this reduction. This could make water saving and uptake of efficient household micro-component appliances and fittings to help with water savings more appealing for households, as the increase in water cost will shorten the payback period of appliances and fittings. Moreover, because water-related energy use and cost are directly related to water savings, any increase in energy costs will increase the cost of an intervention further.

Overall, the AGG scenario performs the best in terms of headroom, but is significantly more energy intensive and costly as a result of the CAPEX required. The ALT scenario performs almost the same as the BAU (1 LCD saving) in terms of demand and performs only slightly better in terms of headroom, at a considerably higher cost and energy use. If the current negative population trend continues, the BAU scenario will be the best option. However, if the population increases then the ALT or AGG scenario may become the best interventions to implement depending on the WSPs objective(s).

Sensitivity analysis was carried out to assess the impact of increased demand on the three scenarios with respect to PGR of 0.2, 0.5, 1 and 2% (in line with typical PGRs in Europe) to determine which scenario will be more appropriate under different PGRs (Figs. 2, 3, 4 and 5). The results show that water demand only decreases at the -0.2 and 0.2% PGR in all three scenarios. However, despite the 0.2% and consequent decreasing demand, energy use and cost increase in all ALT and AGG scenarios.

At PGR 0.2% demand marginally increases in BAU and ALT scenarios as a result of which headroom decreases. Demand increases at almost the same rate for BAU and ALT scenarios as there is only 1 LCD difference in water savings between the two. However, headroom decreases more in BAU than in ALT scenarios due to the water savings achieved from GWR and RWH in ALT scenario. For the AGG scenario at 0.2%, demand decreases until the last interval (2040–2050), as a result of which headroom decreases in the last interval.

Energy use increases in the ALT and AGG scenarios even with the negative PGR and improved energy efficiency of current GWR and RWH systems. Energy use and cost increase in all three scenarios at PGR 0.2%. Although demand is actually decreasing in the AGG scenarios, cost increases due to both population growth and the CAPEX of the

scenario. Both cost and energy use increase substantially more in ALT and AGG scenarios than in BAU scenario for most of the PGRs (Figs. 2-5.), with the exception of both cost and energy use decreasing in PGR -0.2% and energy use decreasing at PGR1%. The difference in cost and energy use increase between BAU – ALT and between ALT – AGG is significant because of the difference in CAPEX and water saving between the scenarios. Only 1 LCD is saved between BAU and ALT, whereas 30 LCD is saved in between ALT and AGG scenarios.

At PGR 0.5, 1 and 2%, demand increases in all three scenarios, the same as at PGR 0.2% but only at a higher rate. The highest increase in demand is in the BAU scenario at PGR 2% where demand doubles at 2030 and increases 4 fold to almost the full supply capacity of the WDS at the end of the planning horizon. This indicates there will be significant implication for the security of future water supply in BAU and ALT scenario if no further action is taken. In the AGG scenario, headroom decreases only by around half at the end of the scenario at PGR 2% as a result of the water saving (30 LCD) that is made from 418 ML/year to 38 ML/year in BAU and 87 ML/year in ALT at PGR 2%. Although this indicates an increase in demand, it is not an immediate water security issue as the WDS will still have the capacity to produce a third more water that it is currently producing. At all positive PGRs, water saving is directly proportional to an increase in energy use and costs in the three scenarios because water saving is mostly achieved by GWR and RWH systems which cost more and use more energy.

In all three scenarios the BAU scenario performs the least in terms of water saving and impact on headroom, but performs best in terms of energy use and cost at all PGRs considered. In the BAU scenario, demand only decreases at PGR -0.2% and increases at all the positive PGRs. Demand increases the most at PGR 2 to almost the current full supply capacity of the WDS. However, the BAU scenario performs better in terms of all the performance indicators for the current negative PGR and 150 LCD water use (assuming current conditions remain the same for the duration of the planning horizon). Therefore the BAU scenario will be the best option if current negative population trend continues even without a reduction in per capita water use.

The AGG scenario offers the most water saving at all PGRs considered, but also has the most energy use and cost. However, because of the energy use and cost involved this scenario will only be appropriate at PGR of more than 1%. The ALT scenario can be a compromise between the BAU and AGG scenario in terms of all the performance indicators, but at a relatively higher energy use and cost than in BAU with respect to water savings. However because of the reduction in headroom in the BAU scenario from PGR 0.2%, the ALT scenario will be the most appropriate to consider for PGRs 0.2% - 1%.
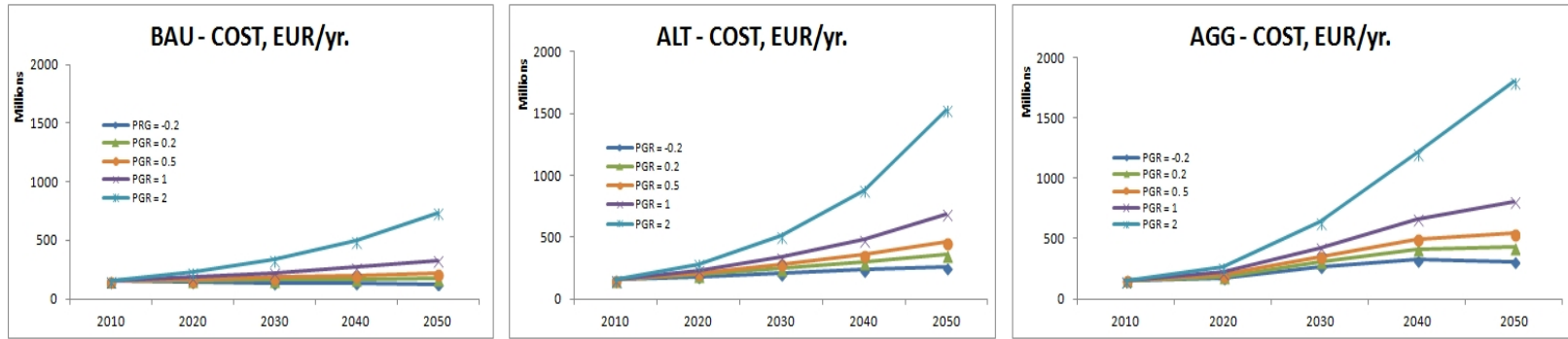
Fig. 2. Sensitivity analysis for the three intervention strategies with respect to cost (EUR/yr)
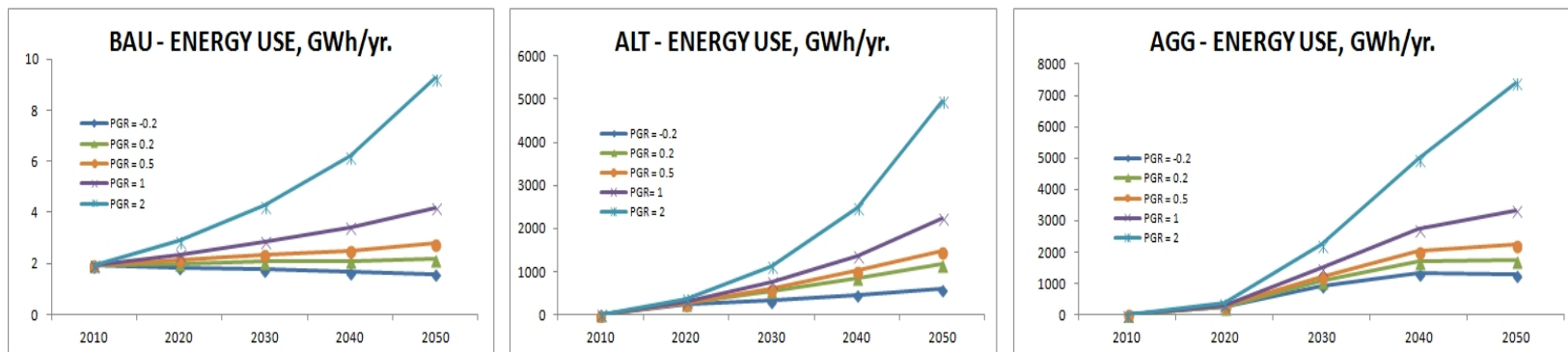

Fig. 3. Sensitivity analysis for the three intervention strategies with respect to energy use (GWh/yr)
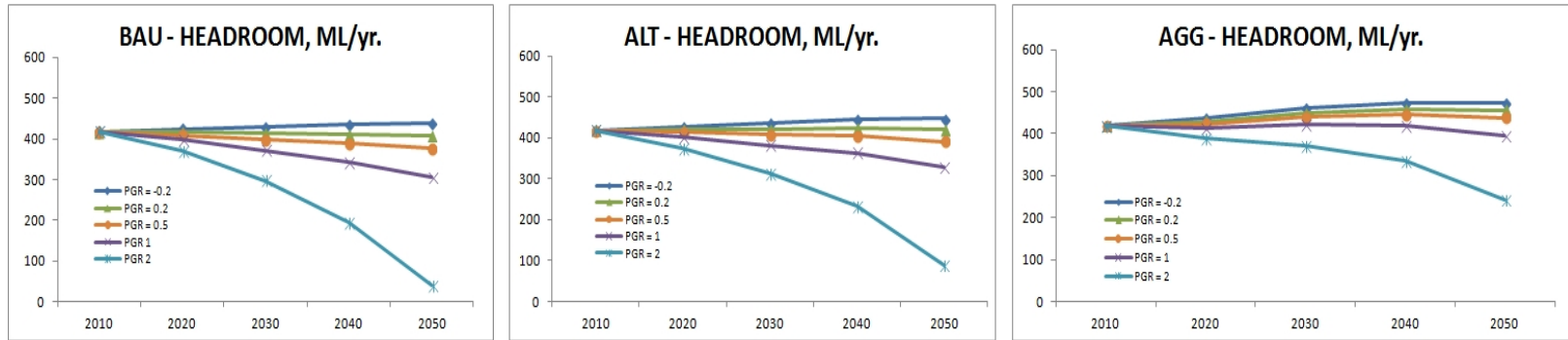
Fig. 4. Sensitivity analysis for the three intervention strategies with respect to headroom (ML/yr)
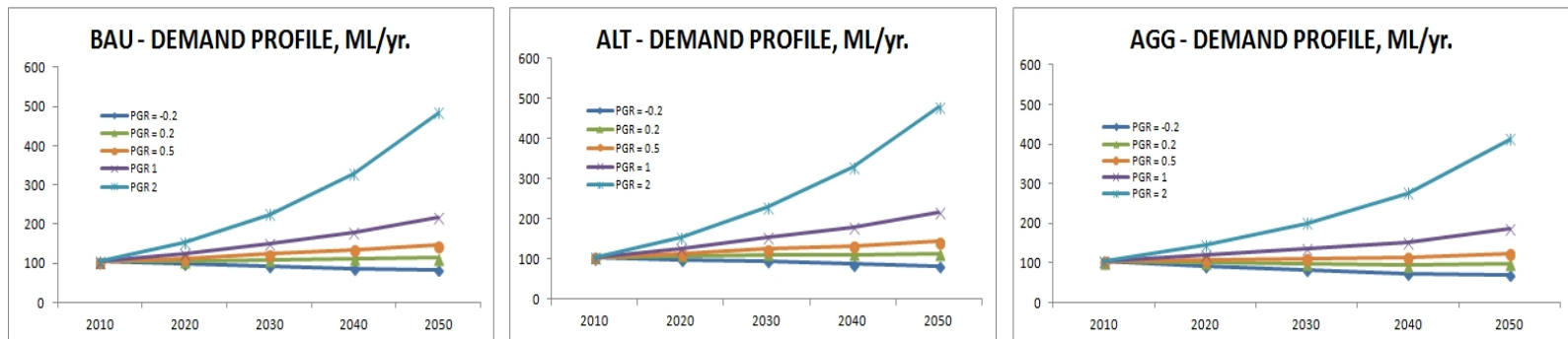

Fig. 5. Sensitivity analysis for the three intervention strategies with respect to demand (ML/yr)

4. SUMMARY AND CONCLUSIONS

WDM interventions are increasingly being used to reduce water use and water-related energy use, reduce cost and negative environmental impacts and have a positive impact on supply/demand balance, whilst still satisfying the needs of consumers. Given that most of the urban water use in Europe is in households, reducing household water use can reduce overall water demand, which can also lead to a reduction in household energy bills, overall water-related energy use, as well as associated GHG emissions and have a positive impact on supply/demand balance. However, not all WDM interventions will result in reduction of water-related energy use and some could increase both energy use and costs.

This paper presented the development and application of a new methodology for the impact assessment of household water savings from different WDM interventions based on their energy use, cost and impact on supply/demand balance on WDS. The methodology has been applied to the case-study of the WDS of a European city using three WDM intervention strategies. The result of the case study shows different degrees of water savings can be achieved depending on the type(s) and proportion of household appliances and fittings considered. Demand will decrease in all three scenarios if the negative population trend continues for the duration of the planning horizon. This indicates adequate security of future supply without any corresponding investment in supply infrastructure. However, a lot of uncertainties could arise over the planning horizon – increase in unit cost of energy and/or water, climate change could impact the availability of water resources and there could be an increase in industrial (i.e. non-household water use) over time or an increase in population and these could severely impact on supply/demand balance and potentially lead to periods of water shortages if no WDM intervention is implemented and/or new supply infrastructure is developed to mitigate this.

Sensitivity analysis was carried out with respect to increasing demand using different PGRs that are representative of PGRs across Europe. The result of the sensitivity analysis indicates although the BAU scenario performs the least in terms of water saving and impact on headroom, it performs best in terms of energy use and cost at all PGRs considered and will be the best option if current negative population trend continues even without a reduction in per capita water use. The AGG scenario offers the most water saving at all PGRs considered but also has the most energy use and cost. However, because of the energy use and cost involved in the AGG scenario, it will only be suitable at PGR over 1%. The ALT scenario is a compromise between the BAU and AGG scenarios in terms of all the performance indicators but at a relatively higher energy use and cost than in BAU with respect to water savings. However because of the reduction in headroom in the BAU scenario from PGR 0.2%, the ALT scenario will be the most appropriate to consider for PGRs more than 0.2% - 1%.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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