KEY VARIABLES AND POLICY TEST TO INCREASE WATER EFFICIENCY IN HOUSEHOLDS IN LONDON: A SYSTEM DYNAMICS APPROACH

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Abstract

Water efficiency is a complex system influenced by different variables. This study focuses in identifying key variables and causal mechanisms to then evaluate policy options to increase water efficiency in households in London. The methodology consists of two phases. Phase one develops a review of previous studies and a focus group session to conceptualize the problem and relationships between variables. Phase two constructs, validates and analyses a system dynamics model, and then proposes policies. Results show promise for reducing water consumption through efficient appliances. However, efforts must be placed in their development. Moreover, installation of metering devices can reduce water consumption, but this effect weakens over time. Occupancy continues to be a major factor influencing water consumption. Because of the study's focus on causal feedback mechanisms, it can explain which policies work and why at other times even by improving balancing feedback loops, the model stabilizes with no further reduction.

Keywords: Households, London, Modelling, System dynamics, Water efficiency.

Introduction

Water is an essential resource for daily activities in the built environment; however, water resources are constrained in many regions (Adeyeye 2014). Establishing a water management plan has become necessary in cities as it is expected that water consumption will intensify in future years as urban populations grow (Adeyeye 2014). The Environment Agency in England and Wales has classified 37 percent of water companies' areas as seriously water stressed, with South East England the most affected (EA/NRW 2013). Thus, there is an increased interest from the UK government to promote water efficiency in households as 52 percent of water is used by this sector (HM Government & DEFRA, 2008). The Government's Water Strategy for England has the objective to reduce water consumption from 0.15–0.16 to 0.12–0.13 m^3 per person per day by 2030 (Defra 2008). However, reaching water efficiency targets can be difficult and counterintuitive because water management is a complex system influenced by variables such as household occupancy, age of inhabitants, perceptions, values, type of building and technology (Robinson, et al. 2014). Hence, to integrate and evaluate different interactions of variables, a system dynamic approach was selected. Previous studies that use system dynamics to assess water management supply and demand, show that the best policy suggests a combination of awareness and low volume water fixtures (Abdi 2009).The aim of this study was to identify the variables that influence water efficiency in households in London, to develop a model that represents the dynamic relationships between these variables and analyse their behaviour, structure and patterns to propose policies.

Water consumption in London

Water consumption per capita in London has varied through time. Water consumption, has increased since 1970 (Thames Water 2009; Thames Water 2014). However, from year 2010, water consumption per capita decreases (Thames Water 2014). Thames Water (2014) projections demonstrated that water consumption per capita in London would reduce because of their water efficiency strategies. The historic variations can be attributed to several factors such as occupancy, metering, frequency of use of appliances and water efficiency.

Metering has been considered a major factor influencing water consumption. Water consumption in metered households [MH] tend to be lower than in unmetered households [UH], this could be due to customer's wastage such as plumbing losses (Thames Water 2014). There is an increased interest in the installation of water meters as a strategy to reduce water consumption. By 2011 in London, only 26 percent households had water meters (Greater London Authority 2011) and it is projected that by 2040 approximately 62 percent of households in London will have a water meter (Thames Water 2014).

Water consumption varies also according to occupancy. High occupancy will increase the total water consumption in a household, but also as occupancy increases water usage per capita decreases (Edwards and Martin 1995). Occupancy in London has been decreasing through time**.** In 2011 occupancy reached to 2.48 and it is estimated that by 2031 it will fall to 2.32 due to an increase in the number of households (Greater London Authority 2015a).

Moreover, the installation of new fittings can reduce the overall water consumption by 25 percent (Sim, et al. 2005). Other studies state that retrofit and behaviour change initiatives can reduce water consumption up to 0.041 and an average of 0.02-0.025 m^3 per day per household (Tipper 2015).

Methodology

The research methodology combined participatory and expert modes of system dynamics modelling. It followed the steps proposed by Sterman (2000) for modelling, which consider problem articulation, model formulation, testing and policy evaluation through an iterative process.

Problem articulation

First, a review of previous studies was performed to determine key variables and relationships with the problem. Second, a group modelling session was carried following the steps outlined in "Scriptapedia", which included graphs over time, dots, and connection circle exercises (Hovmand, et al. 2013) to conceptualize the problem. The model boundaries selected for this model were:

Time horizon: The year 1970 was chosen as the initial year since it is when the charging scheme for water based on house prices started. The model simulates strategies until 2040.

Conceptual and causal boundaries: The exogenous, endogenous and excluded variables were determined by a literature review and can be seen in **Table 1**.

Endogenous	Exogenous	Excluded
• Appliances and their water efficiency • Reduction in water consumption • Optional metering rate • Water demand • Awareness • Leakage	• Size of household • Occupancy • Income • Water charges • Compulsory metering rate • Population • Frequency and quality of campaigns • Construction of households	• Climate change • Demographic characteristics • Water availability

Table 1. Conceptual and causal boundaries

Model Formulation

Specific data was obtained to define behaviour patterns and reference modes (Sterman 2000). The model was constructed by identifying relationships between variables, first, through causal loop diagrams, then by stocks and flows. Stocks represent accumulations and define the state of the system at a given period and flows determine the rate of increase or decrease of stocks (Sterman 2000). The model was formulated through equations using qualitative and quantitative data and comparing it with the reference modes. Six factors were considered as the core factors that affect water consumption per capita: occupancy, metering, leakage, water appliances, awareness and water charges. Each factor was mapped and formulated in the model as described below:

Occupancy

Population and number of households were plotted in the model utilizing average rates of population growth and number of households. Data used for these calculations were obtained from the London Datastore (Greater London Authority, 2013; Greater London Authority 2015b). Occupancy was determined as population divided by the total number of households. The variable *multiplier water demand per household*[1] was included as a combination of household occupancy and decreasing water consumption per capita with increasing occupancy.

Metering

To model the metering process, it was considered that the installation of water meters depends on the metering rate which is the sum of optional and compulsory metering rates. Compulsory metering started in 2007, and the rate calculated for this study using Thames Water (2014) data is 1.5 percent of households per year. Similarly, optional metering began in 1995 and the calculated rate is 0.92 percent of households per year (Thames Water 2014). At the same time, the metering rate is influenced by the *effect of goal achievement*. This variable is used to represent the effects of the efforts that are made when companies are far from achieving the target of Metered Households [MH], but once the number of MH is close to the objective, then the metering rate decreases. Moreover, there are remaining properties where it is difficult to install a water meter, particularly because installation is not technically nor economically feasible (Thames Water 2014). To reflect this fact in the model, a limit for the installation of water meters was included via the variable *effect of the difficulty of installation* that represents the increasing difficulty to install water meters as you approach this limit.

[1] In this paper variables of the model are represented in italics.

Leakage

Leakage was incorporated into the model by adding a constant value of annual leakage per household and a fraction of reduction due to accurate detection in MH. Leakage from customer-owned water supply pipes in households without water meter averages 45 litres per household per year, but for MH, this value averages 19 litres per household per year, as leakages are identified with less effort (CIWEM 2013). Therefore, in the model, a reduction of 58 percent of the leakage was considered for every MH.

Appliances

Ownership of appliances, such as bath, shower, washing machine, dishwasher, basin and W.C, was included, to indicate that as ownership of appliances increases, likewise water consumption per capita. Households with high ownership of appliances are likely to have more occupants and probably bigger homes compared to the ones with low ownership (Parker and Wilby 2013). The variable *available floor area per household effect on ownership of appliances* was used to determine the *ownership of appliances*. This variable represents the effect that the more available floor area, then the more ownership of water appliances per person.

Changes in water consumption characteristics of appliances was modelled as shown in Figure 1. When a new appliance is installed, it flows into the stock of *total appliances*. After an average *time to replace* of 10 years, a new appliance is installed. Whenever an appliance is installed, its efficiency is noted. This behaviour was incorporated using a co-flow of water consumption characteristics so that the *total water consumption by appliances* and the *average water consumption per installed appliance* can be calculated. Households can install ‘normal’ and ‘efficient’ appliances. In addition, both types of appliances have increased their water efficiency over time, decreasing *water consumption per new normal efficient appliance*. This behaviour was incorporated using rates of improvement for *water consumption of new normal efficient appliance*, shown at the bottom of Figure 1. Thus, *average water consumption per appliance* was considered to vary through time depending on the average *time to replace* of 10 years. A second mechanism affects the *average water consumption per appliance*: an additional inflow to the *total consumption by appliances* indicates that appliances age and lose efficiency over time before replacement.

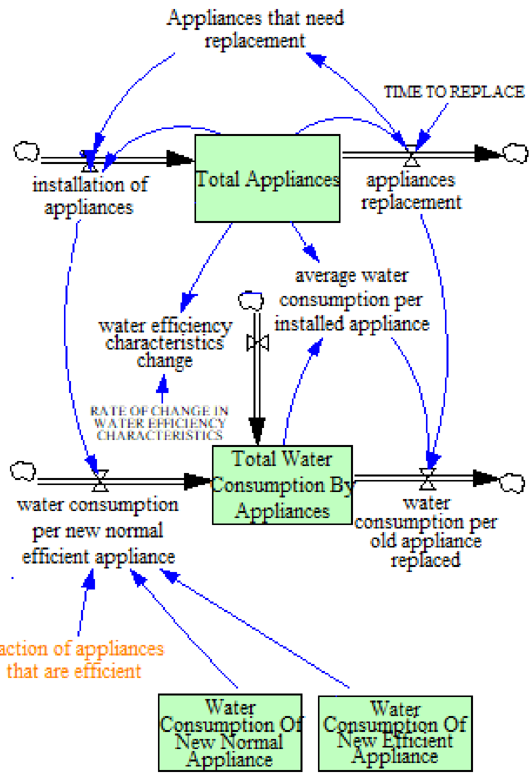

Figure 1. Improvement of water efficiency

The decision process of customers to choose an efficient appliance [EA] versus a normal appliance was defined as the multiplication of the *effect of awareness on the good will to install EA* and the *effect of water cost on opting for EA*. The variable *effect of water cost on opting for EA* takes into consideration a cost-benefit analysis, and it underlies that if the cost of EA is the same as the cost of a normal appliance then there is a probability that 50 percent (Bailey 2014) of people will choose an EA, but if the price of EA higher then this percentage reduces and the decision will depend on cost-benefit analysis. It was included in the model that being environmentally conscious and having environmental values could increase the uptake of efficient technology by 0.09 on average when they have to replace their water appliance (Millock and Nauges 2010).

Then *water consumption of appliances per household* was calculated using the frequency of use of appliances, number of appliances per household and the average water consumption characteristics per appliances. Frequency of use of appliances was determined considering changes in frequency of use in bath and shower events, as changes in frequency of usage of other water appliances are consider to remain almost flat over time (Market Transformation Programme, 2011; Thames Water, 2014) further studies should be made to determine changes in frequency of usage of other appliances.

Awareness

Water metering increases awareness of water consumption, and awareness enhances the number of households opting for the installation of water meters. In the model, it was considered that only a fraction of the population would change their behaviour because of awareness, since not all the population is exposed to the same campaigns. Accumulated awareness of MH and unmetered households [UH] depend on the *frequency of campaigns* and the *rate to forget awareness*. During base run, these values were assumed to be a campaign with a duration of 1.2 months every two years with a rate to forget awareness of 0.6 for MH (meaning that only 40 percent of the campaign is remembered at the end of the year) and 0.7 for UH[2]. Effect of awareness on water usage in both MH and UH was connected to the variable *water consumption of appliances per household*, to represent a relationship where the more awareness the lower frequency of use of appliances.

Water charges

Average income was used to define the percentage of income spent on the water bill. It was considered as a typical expenditure if households spend 1.6 percent of their disposable income on water bills (Ofwat 2011). To determine if people will be willing to reduce their water consumption, the variable *acceptable ratio water bill income* was introduced. If the gap between *acceptable ratio water bill to income* and *ratio water bill to income* is negative, then people will be willing to reduce their water consumption, but if this gap is positive then people will not reduce their consumption, on the contrary, it will increase. However, it is important to underline that change in water usage could be uncertain due to water consumption inelasticity. For the base run it was considered that the maximum reduction in water usage due to water charges can be 5 percent (Herrington 2007).

Causal loop diagram

The overall model was constructed based on the causal loop diagram shown in Figure 2. It gives a high-level overview to complement the earlier description of separate elements of detailed structure and was constructed using information found in previous studies and in group sessions, giving a more comprehensive picture than can be found in other studies. The analysis reveals three major feedback loops. It shows that adopting efficient technology will depend on *awareness* and the benefit that adopting an efficient appliance could have on reducing the water bill, but at the same time, if a household reduces its *water consumption per capita* and its *water bill*, the *fraction of appliances that are efficient* will reduce too, creating a balancing loop (B1), as the perceived benefit reduces. Similarly, another balancing loop was created, B2, where the *fractional change in water consumption habits* influence the *water consumption of appliances per household* and therefore water *consumption per capita* and *water bill*. *Awareness* also plays a significant role; it could affect the *fractional change in water consumption habits* therefore reducing *water*

[2] The units of these rates are dimensionless (forgotten awareness units/ total awareness units)

consumption per capita. In addition, it can increase the installation of water meters (*metered households*) and simultaneously, *metered households* can increase *awareness* creating a reinforcing loop (R1). Finally, *water consumption per capita* will be influenced directly by the variables *occupancy*, *water consumption of appliances per household* and *leakage*.

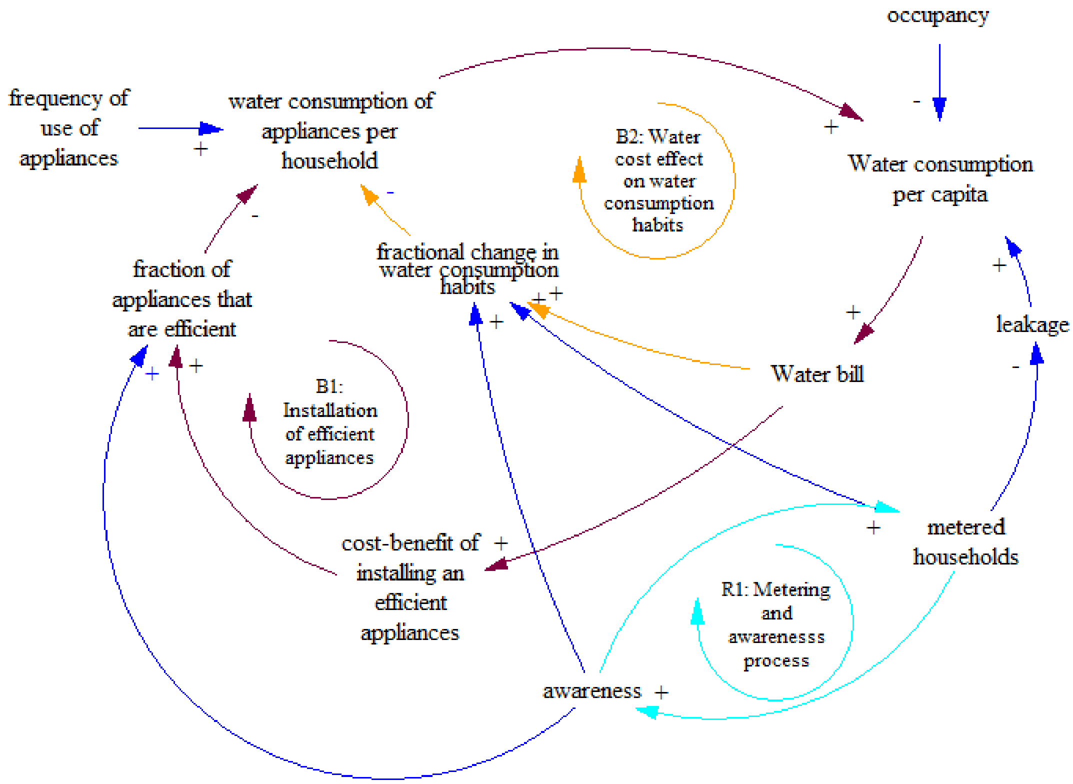

Figure 2. Causal loop diagram constructed from previous research and group session

Testing and validation of the model

Three types of test were performed: behaviour-reproduction test (to determine if the behaviour of the model represents the historical behaviour), extreme conditions (to determine if the behaviour of the model is logical after it is simulated with extreme conditions), structure and parameter assessment (structure, parameters and numerical values correspond to concepts and real life systems) and dimensional test (to identify coherence of the formulations through dimensional consistency) (Forrester and Senge 1980).

Structural validity was also tested in a validation session with the participation of the second author (who is an academic expert on the topic and was not involved in model building) and Aaron Burton (who is a technical expert from Waterwise). This group session consisted of an explanation of the model structure and behaviour over time, and a discussion of the relationships between variables. The comments and suggestions of this session were incorporated in the model.

Policy simulation:

Finally, the dominant mechanisms of the model were analysed. Six policies were selected for simulation. Policy 1, 2, 3 and 4 were suggested by Waterwise (Burton 2016), and policy 5 and 6 were assessed to evaluate their effect on *"water consumption per capita"*, then these policies were combined to obtain a higher reduction:

- Policy 1: Metering for all users and switching to measured tariffs.
- Policy 2: Introduction of informative water bills, targeted awareness campaigns, public education programmes and promotion of water efficient appliances.
- Policy 3: Promote research for new technologies.
- Policy 4: Replace water-wasting appliances and fittings and provide retrofit kits.
- Policy 5: Incorporate a water-energy nexus to increase uptake of efficient appliances.
- Policy 6: Increase common water usage areas.

Results and Discussion

Structure of the model analysis

During the structure of the model analysis various governing mechanisms were identified. First, water meters influence awareness and awareness help reduce water consumption and at the same time awareness increases the metering creating a reinforcing feedback loop (R1). Installation of water meters is also influenced by two balancing loops that demonstrate the difficulty to install water meter and the effect of goal achievement.

As mentioned before, water consumption of appliances change as old appliances are replaced by new appliances. These changes in water consumption create a balancing feedback loop that improves water efficiency in appliances. Also, another important balancing feedback loop related to the installation of EA was identified. At first, if *water consumption in MH* is high, then installing an efficient appliance will be economically attractive, but as water consumption decreases, the benefit of installing a water efficient appliance will be driven down and the *fraction of appliances that are efficient* will also decrease.

Behaviour of the model and analysis

Through the incorporation of the variables and formulations, the following behaviour was obtained for water consumption per capita.

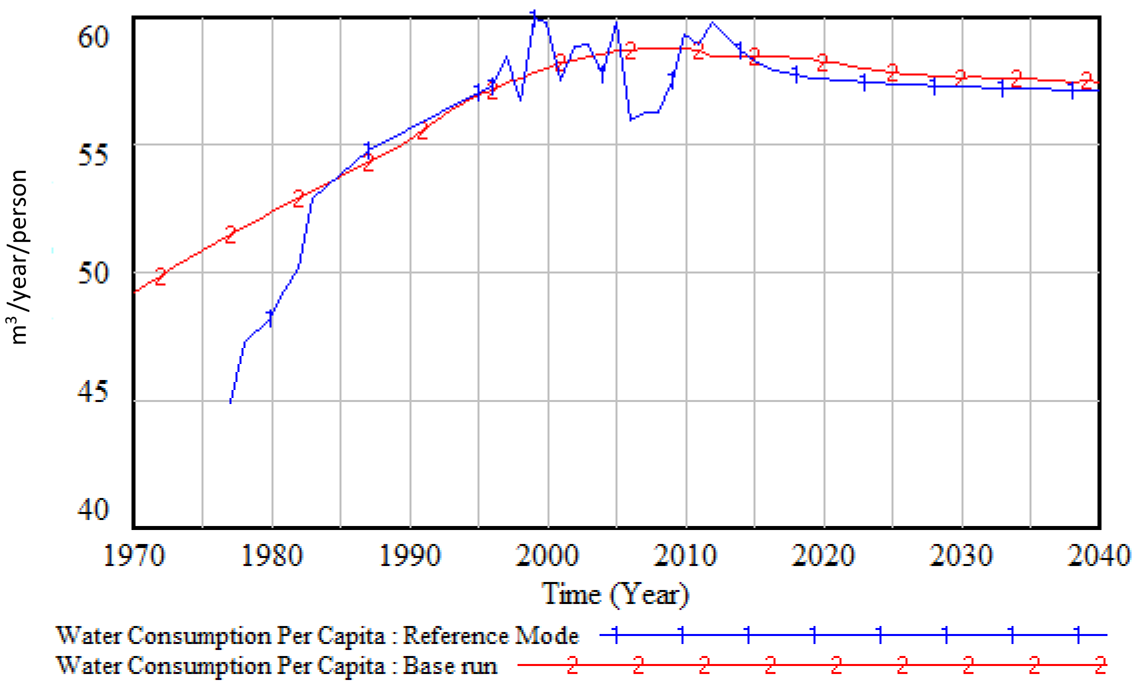

Figure 3. Water consumption per capita

Figure 3 exhibits how simulated water consumption per capita has increased since year 1970 until year 2010, and then it decreases reaching stabilization. This behaviour sufficiently replicates the reference mode.

The main findings from the model were:

Finding 1: Water metering influences awareness and indirectly increased awareness, reduces water use per household. Metering was identified as a relevant variable, however, its effect in water consumption in the long term tends to stabilize, with no further influence in water reduction. This behaviour can be attributed to different feedback loops created in the model. R1, mentioned before, is a reinforcing loop that demonstrates how as more metered households are in London, more is the awareness on water consumption, reducing the usage of water and increasing the awareness in future water meter optants. However, two balancing loops stabilize this growth by reducing the metering rate and new metered households. In overall, an s-shaped growth is created, where the installation of a water meter has been straightforward and also the increase in awareness and its effect in water reduction, however, it reaches a limit where it stabilizes. This behaviour can also be compared with Senge archetype "Limits to growth", there is a growing action (installation of water meters) that increases a condition (*effect of water meters on awareness* and *effect of awareness in water usage*), but there is also a slowing action (*effect of goal achievement* and *difficulty to install water meters*) that controls this growth (Senge 2006).

Finding 2: Awareness in MH is influenced by the installation of water meters, but it is also influenced by the exogenous variable *"frequency of campaigns"*. Contrary, awareness in UH is only affected by the variable frequency of campaigns. Effect of awareness in water usage in both MH and UH resulted in an oscillating behaviour due to the frequency and duration of awareness campaigns. With time, there is a slight increase in awareness in response to the accumulation of awareness. The awareness is stronger in MH particularly because of the presence of water meters that could be a constant reminder of water consumption.

Finding 3: Appliances were determined to be a significant factor that influence water efficiency as there are various endogenous variables and feedback loops that dominate the system. At the beginning water consumption in appliances is high due to number of old appliances in households, but then average water consumption decreases as more efficient appliances are in the market.

There are other dominant mechanisms governing the behaviour of water consumption of appliances per household, which influences water consumption of appliances to increase at the beginning and then to slowly reduce. A balancing mechanism was created, in one hand, water consumption per appliance decreases but on the other hand number of appliances and frequency of use increase. Advantages of replacing old appliances for more efficient appliances is delayed due to *time to replace* appliances which was fixed to be 10 years.

There is another balancing mechanism created, which at the beginning encourages people to use efficient appliances but it becomes weaker when increased efficiency reduces water consumption costs lowering the incentive to move further towards efficient appliances.

Finding 4: Occupancy was determined to be one of the principal factors affecting water efficiency. A variation of occupancy to 2 occupants per household increases water consumption by 13.26 percent in 2040, and a variation of occupancy to 3, reduces water consumption by 13.52 percent. However, occupancy is an exogenous variable in the model and it is difficult to change as it could be affected by other factors such as number of households, income, and population. Though, this motivated the inclusion of a policy that approximates higher occupancy through an increase in common water usage areas.

Finding 5: Water cost to income ratio was always below 1.6, showing that, water cost in London is less than the typical value payed in UK and in other countries, therefore little effect was observed on water consumption. Also, water cost affects adoption of EA, as the economical perceived benefit reduces the attractivity of opting for EA (Finding 3)

Simulation of policies:

Results of the policy simulation are shown in Figure 4. Policy 1 [Metering for all users and switching to measured tariffs] showed that increasing MH will not reduce water consumption significantly in the long term, since the installation of water meters does not guarantee that consumers will be aware of how much water they are consuming. Policy 2 [introduction of informative water bills, targeted awareness campaigns, public education programmes and promotion of water efficient appliances], showed that there is a slight decrease in water consumption as the effect of awareness in water usage and good will to install efficient technology increases. The implementation of each policy independently will not cause a significant variation in water consumption per capita. This behaviour can be explained by the structure of the model, where the reinforcing loop R1, is weak when Policy 1 and 2 are simulated independently and therefore, the effect of awareness on water usage is not enhanced. To enhance this feedback loop, policy 1 and 2 were combined, and the results show that there is a decrease of 4.6 percent in water consumption per capita. This value is similar to the results of previous studies which indicate that awareness and metering could reduce the water consumption in a range from 5 to 15 percent (Critchley, et al. 2015). Though, this reduction tends to stabilize through balancing loops and the reinforcing loop R1 becomes weaker with time.

Furthermore, simulation of policy 3 [promote research for new technologies], shows that there is a reduction in water consumption, as market appliances become more efficient. However, this decrease depends on the replacement rate, and the effects are more significant in the long term. Policy 4 [replace water-wasting appliances and fittings and provide retrofit kits] showed that by reducing the time of replacement of appliances there is a reduction in water consumption per capita. Updating water appliances with more efficient equipment decreases water consumption per capita because it accelerates the benefits of new technology.

Moreover, Policy 5 [incorporate a water-energy nexus to increase uptake of efficient appliances], showed that there is a significant reduction in water consumption per capita by establishing additional economic benefit of installing EA. However, this results only concern to appliances that have both a reduction in water consumption and energy. In this case, the model assumes that all customers are aware of this benefit. Therefore, this policy requires both labelling products and raising awareness. Policy 3, 4 and 5 were analysed as a combined policy. The combination of these policies resulted in 3.76 percent of reduction, but also water consumption per capita tends to stabilize due to the fact that, as the cost-benefit reduces, the good will of installing efficient appliances reduces too, stabilizing the behaviour. Policy 6 [increase common water usage areas] was simulated, suggesting the creation of common areas of water usage to imitate the effects of an increased occupancy.

This simulation indicates that there is a relevant decrease in water consumption per capita as a result of lowering the number of appliances per household.

Finally, a combination of all policies was simulated. This combination resulted in the highest water consumption reduction, decreasing it by 4.91 percent. As mentioned before previous studies that use system dynamics to assess water management supply and demand, showed that the best policy consisted in a combination of awareness and low volume water fixtures. There is not further significant reduction as water consumption per capita reaches a stabilization. By comparing the "combined policy" and a model simulation with a constant occupancy of 3 (Figure 4) it could be seen that the combination of policies can decrease water consumption significantly, however, regarding water consumption per capita, the reduction is not as significant as with an increase in occupancy to 3.

Moreover, this simulation does not reach the targets of reducing water consumption per capita to 43.8-47.46 m^3/year established by UK government (HM Government & DEFRA, 2008), suggesting that water efficiency goals should be attained by additional strategies. Further strategies can be focused on developing policies that promote high occupancy water consumption per capita levels, as creating more common water usage areas or promoting laundry services.

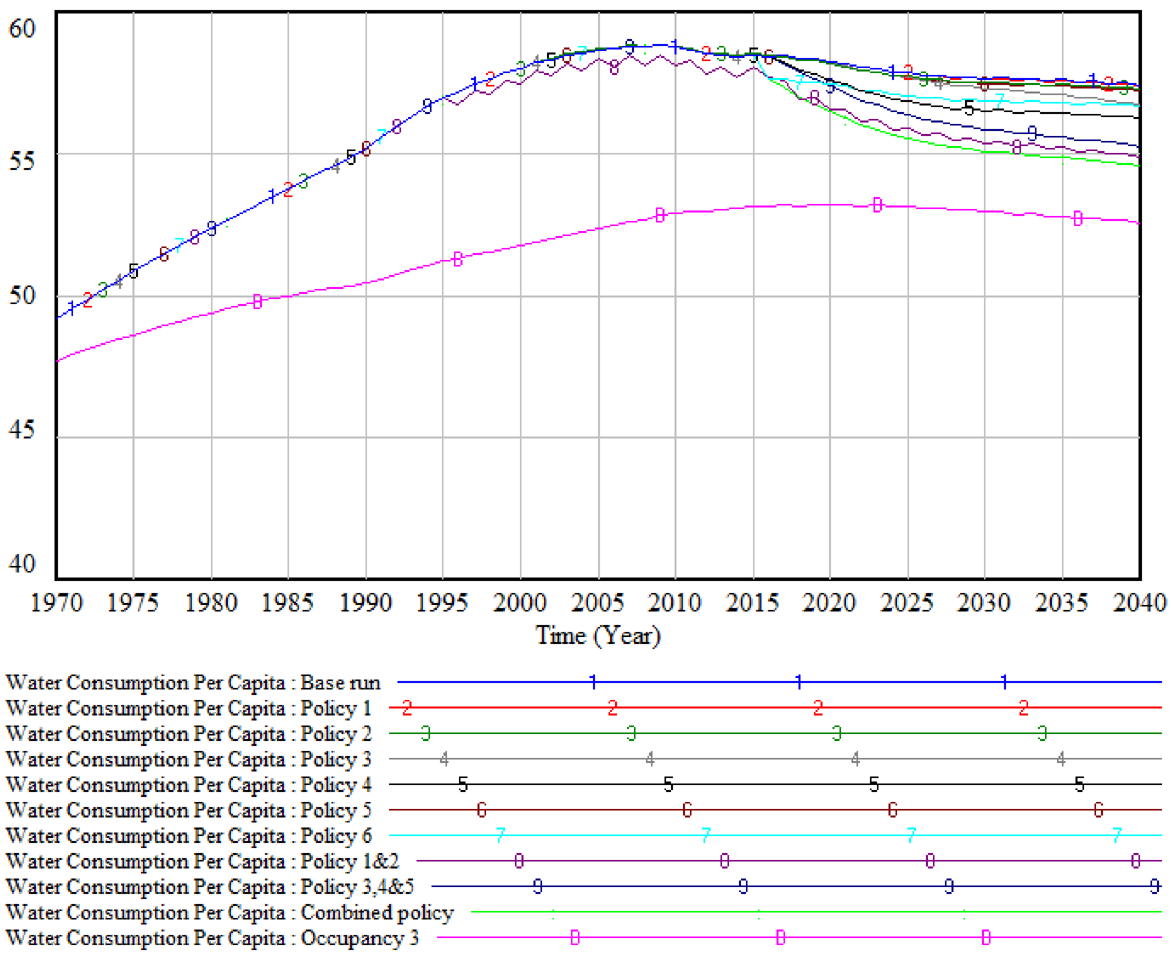

Figure 4. Water consumption of appliances all policies and occupancy equal to 3

Conclusion

Metering was determined to be a useful tool to increase awareness and reduce water consumption, but it is important to notice that in the long-term water consumption reduction due to metering tends to stabilize, as the reinforcing loop governing the behaviour tends to become weaker with time. This suggests the implementation of other policies. Awareness was determined to be important for enhancing the effect of other variables in the model. For example, if water meters are installed without awareness campaigns, then the reduction of water consumption is lower compared with both policies implemented together.

This model showed that promoting efficient appliances is a promising sector for reducing water consumption. However, effort must be placed in the improvement of efficiency and replacement time of old appliances. Results showed that a combination of policies led to the higher reduction of water consumption, however, it does not reach expected targets as water consumption per capita stabilizes over time. Stabilization was reached due to balancing feedback loops, where a “limits to growth” behaviour was identified. This behaviour was seen especially in the installation of appliances where the higher the efficiency, the lower the water consumption and the water bill, therefore reducing the likelihood of installing efficient appliances in the future. Also, findings from the model showed that at the end occupancy is still a major factor influencing water consumption. By comparing the “combined policy” and a model simulation with a constant occupancy of 3 it could be seen that the combination of policies can decrease water consumption significantly, however is not as much as an increase of occupancy of 3.

Moreover, even by improving balancing feedback loops the model stabilizes, with no further reduction. Most of the policies are based on “good will” and “cost-benefit” motivations and it could be said that consumption tends to stabilize when consumers have reached an “acceptable water consumption”.Other urban planning policies could be tested and implemented, to try to imitate high occupancy water consumption per capita levels.

System dynamics constituted a useful methodology when trying to evaluate water efficiency as a system and to suggest policies that could affect or not water consumption. Further research could be done using system dynamics approach with continuous expert validation, especially during policy formulation to shape achievable policies. Studying water efficiency using system dynamics highlights the importance of considering the complex relationships between variables to avoid counterintuitive effects before, during and after the policy formation process.

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World Count

5386

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