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# Agent-based modelling to simulate the socio-economic effects of implementing time-of-use tariffs for domestic water

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A R T I C L E I N F O

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A B S T R A C T

Designing and implementing innovative and effective policies to reduce domestic water demand is vital to enhance sustainability of cities. Past research has shown that Time-of-Use Tariffs (TOUT) is a powerful tool to reduce water consumption in urban settings. Nevertheless, the effectiveness of this dynamic water pricing approach might be influenced by the socioeconomic conditions and preferences of households. To shed light on this issue, this paper employed an agent-based modelling method to simulate the possible socioeconomic effects of implementing TOUT in a Spanish municipality. The types of households were characterized according to size, number of inhabitants, income and to socio-cognitive profiles (clients, techno-solutionist, committed and environmentalist). Results from the modelling indicate that the implementation of a TOUT system would reduce domestic water use by 17.2%. However, this reduction was not homogenous for the socioeconomic groups of households defined. Low-income households are those who most reduced their water consumption (25.0%) but had the lowest water bill savings (9.3%). By contrast, high-income households present the largest water bill savings (11.9%) but the lowest reduction in water use (10.4%). The findings of this study evidence the importance of considering the socioeconomic and socio-cognitive differences among water users to evaluate the effectiveness of TOUTs.

## 1. Introduction

Many factors threaten water resources, such as climate change or the pollution of groundwater and surface flows. Moreover, the world population growth combined with the spread of new lifestyles in the developed world, (i.e., smaller homes with fewer residents, making water savings through economies of scale more difficult), increase aggregated water demand, even if *per capita* consumption has been generally declining in some cases (Perello-Moragues et al., 2021; Ebrahimi et al., 2022; Li et al., 2022). Forty percent of the world's population is facing water scarcity and over 1.7 billion people are currently living in river basins where water use exceeds recharge (United Nations, 2015). Worldwide, the access to water and sanitation is significantly unequal.

Water scarcity may be addressed from multiple policy angles, which range from the environmental to the economic. New technologies can be a great ally for both preserving water sources and ensuring universal access to quality water. The Water 4.0 paradigm (Sedlak, 2014) encapsulates this idea, as water management aspires to be more resource-efficient, flexible, and competitive, by improving water infrastructures, minimizing waste and increasing water availability via alternative water sources such as water reuse or storm water capture. The use of smart technologies can lead to the connection and data exchange between all the actors and infrastructures in the water sector (Kosolapova et al., 2021). Moreover, Water 4.0 implies an enabling environment for decentralized water management systems, with the support of digital solutions such as the internet of things (IoT), Big Data and analytics, cyber-security, cloud platforms and artificial intelligence (AI), and machine learning (ML) (Alabi et al., 2019). However, implementing these technologies may have unexpected impacts (March et al., 2017; Moy et al., 2019), which need to be carefully assessed.

One of the digital technologies that is gaining increasing popularity in the current water management paradigm is the smart water metering,

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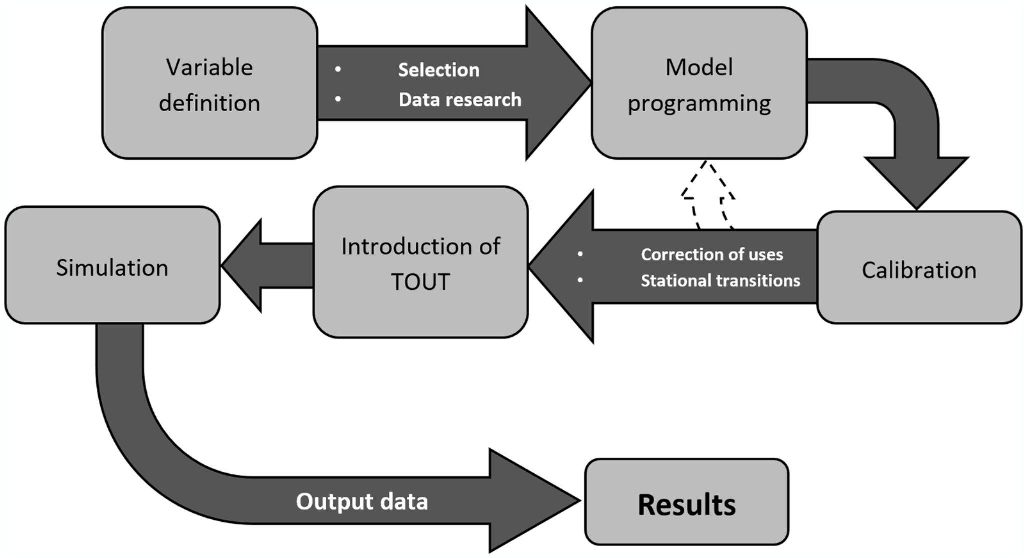


**Fig. 1.** Main steps for the development and use of the ABM presented in this paper.

as a useful tool for the dynamic pricing of water (Cole et al., 2013; Moy et al., 2019). In this sense, Cole et al. (2012) present Time-of-Use Tariffs (TOUTs) as a way to improve efficiency in water use. In this tariff scheme, water prices depend on the time water is consumed, with existing pre-set time slots with fixed prices for each. Some benefits associated to TOUTs, based on smart metering, could take the form of a redistribution of urban water consumption throughout the day (Cole et al., 2013). This would help to reduce network stress caused by high pressures at certain times of the day and produce a more regular flow reception in wastewater treatment plants, for example. However, to what extent does this pricing method contribute to a reduction in urban water consumption? Vašak et al. (2014) state that a dynamic water pricing would lead to a decrease in the water utility costs (5.28%) as well as in consumers' billing (5.25%). In a similar vein, Rouge et al. (2018) design dynamically priced tariffs based on two different time scales. Focusing on a case-study in London, these authors use sub-daily price variation for peak management and monthly or weekly variations to deal with scarcity. They maintain that this kind of tariff could help reduce environmental flow shortages in their case study by approximately half (22-63%) and network savings of £200 per property (3.3 million) in net present value. Furthermore, they show how residential price increases for consumers are limited, as the price doubled less than 2% of the time in their models. Both studies use a design methodology for dynamic water pricing and analyse its effects in terms of cost and water savings. The analysis of water demand and its (in)elasticity is based on gathered data (Vašak et al., 2014) or represented by equations (Rouge et al., 2018), which consider the whole population as a homogeneous responding as a block to the implemented tariff changes. These studies overlook aspects which are key in water demand policies: not everyone shares the same reasons for saving water and moral values play an important role in the way people take decisions.

Values can be defined as the mental framework from which humans set their own vision of the world in terms of what is good or desirable and what is not (Schwartz & Bilsky, 1987). Values not only affect individual behaviour, but they are constitutive of any societal construction. According to Perello-Moragues et al. (2021), the water-saving behaviour will differ according to each consumer "value profiles". For instance, some people will be more inclined to pay for less water-consuming technologies in order to avoid actually changing their water consumption habits.

Agent-based modelling (ABM) has proved to be a useful method for social simulation especially for public policies design purposes (Gilbert & Troitzsch, 2005). This tool is able to capture and represent the complexity of human behaviour and the dynamic interaction of individuals with each other and with the 'world' in an artificial environment. The model relies on 'agents', which are computational entities programmed with AI to act independently and according to pre-set interests. At the same time, actions by agents can be influenced by (1) their experience, (2) other agents and (3) their environment. For reliable results, it is crucial to understand the relationship between many different variables such as – in our case – consumers' value profiles, types of households or income.

Note that the potential of ABM is not to produce future predictions (Galan et al., 2009a), but to offer a framework for understanding the effects of certain events and the internal logics of the studied social phenomena. In the words of Galán et al. (2009b), "our aim is not to provide short-term predictions, but to gain long-term understanding". Agent-based social simulation (ABSS) and ABM have already been used to study public policies (Gilbert et al., 2015) and changes on urban water consumption. In the case of the latter, they include urban water demand modelling (Koutiva & Makropoulos, 2016; Wang et al., 2021), studying the impact factors such as climate, population growth and water shortages have on water supplies (Mashhadi et al., 2017), and also the diffusion of water-saving innovations (Schwarz & Ernst, 2009).

Against this background, the research questions addressed in this study are as follows: What are the benefits and the negative impacts generated by the TOUT dynamic pricing method? To what extent does this method trigger agents motivated by economic reasons to change their habits when they were reluctant to do so at the current rates? The main objective of this study is to evaluate the influence of socioeconomic conditions and preferences of households on the effectiveness of employing TOUTs as a dynamic pricing system. More specifically, the study brings new empirical evidence to quantify the extent to which efforts made by users to decrease in consumption achieved by TOUTs may outweigh the benefits of water savings.

Using ABM, this paper offers a novel perspective on the analysis of smart water solutions, by taking into account a scarcely studied aspect of the TOUT policy option: the human behaviour. To do so, we include socio-cognitive aspects – moral values – in the programming of agents, to assess policy options in the water domain. Therefore, the paper aims to contribute to a better understanding of the interplay between human behaviour, technology, and water management in general.

## 2. Material and methods

The methodological approach followed in this study is summarized

**Table 1**
Model variables.

| Fundamental variables | Internal variables | Consumption variables | Decision making variables |
|---|---|---|---|
| Basic unit of agents<br>Number of agents<br>Simulation intervals | Household type<br>Household members<br>Household disposable income per capita | Uses<br>Consumption<br>Frequency<br>Distribution | Values<br>Social network |

in Fig. 1.

The model presented in this work represents a city consisting of multiple households. Each of these households make certain water uses. Each water use has an associated volume and frequency. Regularly, households receive information about their water consumption, the source of the water and its price (water tariff). This information determines their decision to reduce, or not, their water consumption. If the decide not to save water, their water uses remain the same. However, if they decide to reduce their water consumption they will perform certain actions, depending on their profiles, to reduce certain water uses, the frequency with which they perform some of their water uses or both. Subsequently, households use water remains unchanged until they are provided with new data which initiates another decision-making process.

### 2.1. Time-of-use tariff proposal

The TOUT proposed in this study distinguishes between three types of time slots (ranging from the cheapest to the most expensive): off-peak, mid-range and peak. In the model, the prices of each section follow the system of volumetric block tariffs. The main goal of implementing TOUT is to achieve water savings, not to increase the financial benefits of the water company. Hence, this value remains the same. The original price of the blocks from the volumetric tariff undergoes a slight variation to ensure that the water company's revenue does not change. As will be explained later, the length and position of each time slot is chosen in the calibration process.

A key factor when proposing changes to water tariffs is the inelasticity of urban water demand, especially for indoor uses (Arbues et al., 2004; Cole et al., 2012). Consequently, in our model, lower income households reach a point where they cannot take actions to reduce their water use even if the water bill increases, as this would endanger fulfilling basic needs. Moreover, in the case of wealthier households, economic measures alone may not be sufficient to persuade them to reduce consumption as these profiles may prefer to pay the higher water bills to maintain their level of comfort.

The paper distinguishes between three types of water uses: (i) essential, (ii) important but changeable, and (iii) unessential. Essential water uses are those which fulfil human needs such as drinking, cooking, using the toilet or handwashing. These uses are considered to be inelastic, i.e., they are unlikely to change irrespective of the variation in the water pricing (Cole et al., 2012). Secondly, there are other uses which are also known to be inelastic, as they are necessary and cannot be avoided (Perello-Moragues et al., 2021), but for which there is a certain margin for deciding the best time of use. In this category we find showering or using the dishwasher and/or washing machine. These are the main uses expected to be influenced by TOUT. Last, there are uses which are considered "unessential" but are also quite inelastic, as they are associated to the built-in features of households and have a symbolic role in society – such as swimming pools and ornamental gardens (Vidal et al., 2011). They represent important investments and play a mainly aesthetic and status-related role in high-income households. Therefore, they may not be easily discarded. Other factors that may hinder a proper analysis of the effects of proposed tariffs are as follows. First, the energy pricing method, which is highly related to water uses (Voskamp et al., 2020) such as the dishwasher and the washing machine or heating water with electric boilers (Fuentes et al., 2018). Second, the so-called "digital divide" – i.e. the disparity in access and ability to use internet services - can be a limitation for certain segments of the population (for instance, the elderly) (Lythreatis et al., 2022) in accessing their water consumption data collected by smart meters and taking decisions accordingly. Unfortunately, this information was not available for the case study and therefore, this paper analyses a scenario which is only conditioned by water pricing as an economic measure for demand management. We are aware that this is a simplification, but it is designed-in to enable the modelling process and shed light on this specific economic measure for water demand management.

### 2.2. Case study description

In this paper, we chose the municipality La Seu d'Urgell (from now on "La Seu") as a case-study for our model. So far, the Spanish literature on urban water consumption has tended to overlook small municipalities, focusing mainly on large cities (Galan et al., 2009b; March et al., 2017) to over one million inhabitants. Nevertheless, the number of cities with just over ten thousand inhabitants is not negligible: according to data provided by the Spanish Statistics National Institute (2021) in 2021, Spain has 213 cities with a population between 10,000 and 15,000 inhabitants. The total population they represent is about 2.58 million, which falls between the number of inhabitants in Spain's two biggest cities: Madrid 3.3 million and Barcelona 1.63 million.

La Seu, located in the Catalan Pyrenees, Spain (see Fig. 3), has 12,000 inhabitants (as of year 2020 (IEC, 2021). Urban water is supplied by a public company, HIULS SA, and its current tariff model follows the volumetric block approach, where consumers' potential consumption is divided into volume blocks and each cubic meter is paid at a fixed price depending on the block. In terms of consumption, according to data from 2011 to 2015, La Seu consumes a mean of 2928 $m^3$/day, equivalent to 168 L/person/day, after adjusting for water losses. That is 26% above the average for Spain in 2018 (INE, 2020). According to the available data from those five years, the month with the lowest consumption was December 2011, with 60,490 $m^3$ (111 L/person/day) while the month with the highest consumption was July 2015, with 131,500 $m^3$ (242 L/person/day).

### 2.3. Conceptualization of the agent-based model

According to the methodology shown in Fig. 1, in the first step of the model design, all the variables taken into consideration have been classified into four main categories, according to the role they play: fundamental variables, internal variables, consumption variables and decision-making variables (see Table 1).

Fundamental variables are those which are key to defining the environment of the model and the simulations running from it. In this case, each agent represents a household, as this is the 'basic' unit from which water consumption is metered and later billed. Following the standard accepted in the literature (Becu et al., 2003; Athanasiadis et al., 2005; Koutiva & Makropoulos, 2016), we used a high scaling ratio of 0.1 which, in our case study, corresponds to modelling 256 household, or 10% of La Seu's total households. In our model, a whole year is simulated through discrete time-steps of 15 min.

Internal variables define the socio-economical characteristics of the households which may be low, medium, or high-density, and they have

**Table 2**
Water uses considered in the model, with their consumption and frequencies.

| | Hygiene (shower) | Dishwasher | Washing machine | Toilet | Hygiene (sink) | Garden | Swimming pool |
|---|---|---|---|---|---|---|---|
| **Consumption** | 36 L/use | 15 L/use | 75 L/use | 5 L/use | 4.5 L/use | 60 or 200 L/d [1] | 155 L/day |
| **Frequency of use (per person)** | 6 per week | 1 per week (per household) | 1 per week (per household) | 5 per day | 7 per day | - | - |

[1] There are two values associated with 50 and 200 $m^2$ gardens of medium and low-density households (1).

**Table 3**
Price of water by blocks and fixed prices on La Seu water tariff.

| Consumption block | Volume (every four months) | Price |
|---|---|---|
| **Block 1** | 0 to 16 $m^3$ | 0.299 €/$m^3$ |
| **Block 2** | 16 to 60 $m^3$ | 0.387 €/$m^3$ |
| **Block 3** | more than 60 $m^3$ | 0.575 €/$m^3$ |
| **Concept** | | **Fixed rates** |
| **Fixed service fee, every four months (excluded VAT)** | | 12.68 € |
| **Water meter rent, every four months (excluded VAT)** | | 3.50 € |

**Table 4**
Catalan water tax price for volumetric blocks.

| Consumption block | Volume (monthly) | Price | Monthly extension per person (> 3 inhabitants) |
|---|---|---|---|
| **Block 1** | 0 to 9 $m^3$ | 0.4936 €/$m^3$ | + 1 m3 |
| **Block 2** | 10 to 15 $m^3$ | 1.137 €/$m^3$ | + 2 m3 |
| **Block 3** | 16 to 18 $m^3$ | 2.8425 €/$m^3$ | + 3 m3 |
| **Block 4** | more than 18 $m^3$ | 4.548 €/$m^3$ | - |
| **Concept** | | | **Price** |
| **Tax minimum, 6 $m^3$ per subscription per month** | | | 0.4936 €/$m^3$ |

from 1 to 4 residents [1]. The proportion of each variable was defined by using data provided by the Catalan Institute of Statistics (IEC, 2021). Income *per capita* is not available for La Seu. Hence, this variable was calculated as a proxy of the Metropolitan Area of Barcelona (MAB) (Ajuntament of Barcelona, 2014). Three levels of income were defined: low (up to €938/ person/month), middle (€938 to €2,502/person/-month) and high (more than €2,502/person/month).

Regarding water consumption variables, households were attributed certain uses, i.e., a volume of consumed water and a frequency of use (see Table 2), which can be either weekly or daily. In a first phase, frequencies of uses are based on data reported in studies of the MAB (Vidal et al., 2011; Perello- Moragues et al., 2021). We subsequently calibrated the data to fit La Seu's consumption pattern.

Uses were also linked to a probability distribution of what time of the day they were more likely to occur. This distribution was based on a fitness proportionate selection (also known as roulette wheel selection) (Lipowski & Lipowska, 2012) for certain hours of the day, where each fitness was determined based on consumption patterns from Aigües de Barcelona (2021) (see Table S1 in Supplemental Material).

The specific case of swimming pools was calculated in accordance with the work of Vidal et al. (2011) who report that the water consumption a swimming pool adds to a house in the Metropolitan Area of Barcelona is 155L/day. As most of these losses are due to evaporation, the water consumption of swimming pools is shown in Table S2 in supplemental material.

Decision-making variables refer to whether households want to reduce their water consumption or not. These decisions depend on socio-cognitive factors and are based on the value profiles proposed by Perello-Moragues et al. (2020): "client", "techno-solutionist", "committed" and "environmentalist" (see Table 6 for more details). These value profiles reflect the moral reasoning behind the household's decision to reduce their water consumption, which can be either economic or environmental. In short, they could be respectively summarized as 'wanting the best for oneself' or 'wanting the best for everyone, oneself included' (Schwartz, 2012).

The model determines the kind of actions agents are allowed to take which, in our case, and following Lam's scheme (Lam, 1999), are restricted to two: device replacement or changing practices. The model also considers the relationships and imitation practices among neighbours. Therefore, each agent is linked to 4, 6 or 8 other agents, depending on the household type. According to Fig. 1, the fourth step in our methodological approach is to consider the current water tariffs in La Seu. As it is shown in Table 3, the structure of the water tariff in La Seu is composed of a municipal fee and a regional tax. Both are based on an increasing volumetric tariff approach. The municipal water tariff is composed of three blocks, each with a fixed price (Table 3).

The regional tax is established by the government of Catalonia and works with blocks of consumption, subsidizing those households with a greater number of inhabitants (see Table 4) (ACA, 2021). Because the regional water tax is defined and implemented by Catalan authorities and therefore it cannot be modified by local authorities, in this study only the municipal volumetric tariff is replaced by a TOUT, while the regional water tax is not modified.

The next step is to program the model, including the variables and the relationships between them. Once this step is accomplished, it is necessary to test if the model programmed according to the established parameters is capable of reproducing the water consumption of La Seu, resembling its shape and magnitude. For this purpose of calibration, successive runs of simulations from the model are used to adjust the water uses proposed earlier, until the model works on a hypothesis which resembles as much as possible the water use habits of La Seu residents, with the section tariff incorporated. The reference data for this calibration was provided by HIULS, the public water company in La Seu. The data used are the daily flows injected into the water network from 2011 to 2015 (see Fig. 4), which is the most recent information HIULS was able to provide us with. Flow usually suffers losses before arriving to the consumers, there "non-revenue water" needs to be considered: a 70% efficiency of the network (HIULS, 2021) was chosen when comparing real data with the simulation results (see Fig. 4).

After a first simulation, the amount of water consumption corresponding to each use was adjusted upwards by choosing the higher amounts related to old devices. Some frequencies were also adjusted by using practical knowledge.

Second, the model was calibrated to suit seasonal change, by adding progressive uses and disuses of pools and gardens, as well as increasing

[1] Note that it is plausible that more than 4 people live in a household. According to IEC (2021), the number people in households in La Seu d́Urgell is as follows: i) households with one member: 1569; ii) households with two members: 1535; iii) households with three members: 1145 and; iv) households with four or more members: 1013. According to statistical data available, it is impossible to know the number of members of the households classified as "four or more members". For this reason, we have to assume that they are four members.

**Table 5**
Final water uses habits attributed to La Seu inhabitants.

| | Hygiene (shower) | Dishwasher machine | Washing machine | Toilet | Hygiene (sink) | Garden | Swimming pool |
|---|---|---|---|---|---|---|---|
| **Consumption** | 72 L/use | 15 L/use | 100 L/use | 6 L/use | 12 L/use | 60 - 120 or 200 - 400 L/d | 155 $m^3$/year |
| **Frequency of use (per person)** | 6 per week (7 in summer) | 1 per week | 1 per week | 6 per day | 10 per day | - | - |

**Table 6**
Characterization of households according to their profile value.

| Values of agents | Clients | Techno-solutionists | Committed | Environmentalist |
|---|---|---|---|---|
| **What determines the will of savings** | Economic savings | Economic savings | Water savings | Water savings |
| **Type of changes** | Devices more than practices | Only devices (can be influenced by neighbours) | Devices and practices | Only practices |

the number of weekly showers most residents take in the summer to seven per week. The most significant change was a higher amount of water used during the summer for garden irrigation. The larger difference that can be seen in Fig. 5 between the real data and the results of simulation 6 is attributed to the water used to irrigate public gardens during that season.

After applying these adjustments to the model, the results obtained are very similar to the real data from La Seu. The average daily water consumption according to the real data is 167.8 L/day/person, while for the model results it is 166.2 L/day/person. Yearly consumptions are also similar, 61.2 $m^3$/year /person according to real data and 60.6 $m^3$/year/person according to the model.

The resulting water-use habits on which the model is based after its calibration are much higher (see Table 5) – both in consumption and frequencies – than those based on the Barcelona Metropolitan Area from which the model was developed (see Table 2).

In addition to the daily volume consumed, the calibration step also included the distribution of water uses throughout the day (see Fig. 5). Since HIULS did not provide data related to the distribution of consumption flows throughout the day, the hourly distribution of consumptions was based on the fitness-proportionate selection (or roulette wheel selection) shown earlier (Table 3). Real data from smart metering would have made it possible to calibrate this distribution as well.

After the model was calibrated to ensure it reflected the urban water consumption of La Seu in a realistic way, the proposed TOUT was introduced into the model. This allowed us to study how household water consumption varied according to the time of consumption.

Each timeslot of the TOUT was chosen by using the distribution of water consumption obtained with the model (see Fig. 6). The price of each slot was the block charge of the current water rate in La Seu including a reduction (See Table S3 in Supplemental Material). Households currently using an amount of water below the first block do not pay any $m^3$ of water at the highest prices, i.e., 0.387 €/$m^3$ and 0.575 €/$m^3$. By contrast, based on the TOUT approach, all households pay water at the three established price slots. By keeping the prices of each time slot, the total amount invoiced by the public water company would increase. As the main objective of the measure is to reduce water consumption rather than increase the water company's profits, a price reduction will be applied to all three segments to keep the turnover stable. To achieve this reduction, iterative simulations were performed until the optimal reduction in water prices was found. Our agent-based model is especially useful in this situation as price changes also have an impact on the behaviour of households and their consumption.

Once the TOUT was introduced, modelled households could receive weekly information of their consumption, and how much their water bill would be if their consumption remained the same for four months. Based on this information, they decide whether to take action to reduce their water consumption or not by 1) changing their water-using devices, 2) changing their behaviour (practices) in order to save water, and 3) combine both. As mentioned earlier, value profiles (see previous section and Table 6) determined the kind of decisions and the actions available to the modelled households. On one hand, households that saved water for economic reasons compared the cost of their weekly consumption projection to the last one, and if it rose, they decided to act to lower their consumption. On the other hand, households that wanted to save water compared their consumption to the average proportion that would correspond to them based on the regular consumption. If they were above that average, they acted to save water.

Households that decided to change their water-using devices for more efficient ones chose them with an order of preference proportionally inverse to the price of the new device (Table S4 in Supplemental Material). It was considered that water use reductions due to the implementation of more efficient devices are permanent, as users are not expected to switch again to the old device after having invested in a new one. Even if they are not as satisfied with those as they expected to be.

The water uses likely to be affected by practice changes were those which have been pointed out earlier as important but changeable. The consumption and frequency that decreased with each practice change remained the same as Perelló-Moragues (2020).

Unlike device changes, practice changes were reversible: thus, if a household was dissatisfied with the change of practices adopted – by not reducing their cost of consumption after three weeks of adopting a practice change – residents could decide to go back to their original practice. However, this was not an option for environmentalist households, as they only can use practice changes to accomplish their objective of reducing the amount of water they use.

It is important to note here that our aim was to explore the extent to which TOUT could be an incentive to save water for households mainly driven by economic motivations (i.e. "clients" and "techno-solutionists") and that are unlikely to consider practice changes. Therefore this option was introduced as an effect of the tariff system. Households with client or techno-solutionist profiles considered changing the time of the day of certain water uses only when they had exhausted all other options for saving water and still had an economical incentive to reduce consumption. Considering the proposed timeslots of the TOUT, the weighted probability of the time they chose to carry out different water uses would change. The differences between probabilities were based on Cole et al. (2012) and a practical knowledge of the urban water supply in La Seu. They are shown in Table S5 in Supplemental Material.

## 4. Results

In first place, after iterative simulations, we estimated a 26.5% reduction in the price of each block when the TOUT approach was implemented. The resulting prices for each time block were the following:

We compared the current water consumption employing the volumetric block tariff with the hypothetical water consumption when

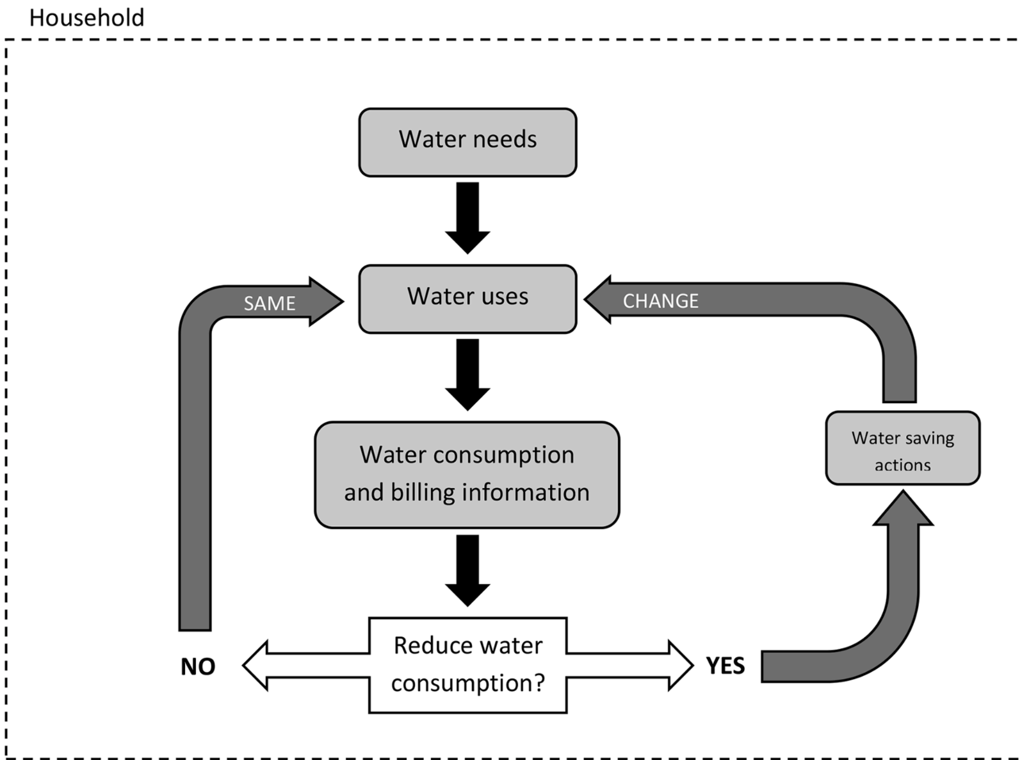


**Fig. 2.** Household process to decide whether to reduce its water consumption or not.


**Fig. 3.** Location of La Seu in the Catalonia region (grey) and Spain.

employing TOUT (see Fig. 7). As can be seen in the figure, we estimated an annual reduction in water consumption of 17.2% with the same seasonal changes.

According to the model, implementing TOUT would involve considerable water savings. However, as mentioned earlier, it is also important to focus on how these changes happen, how they can affect households depending on their house type or income. Therefore, an insight into the changes in households' consumption was also in order (see Fig. 8). As our interest is to determine the social impacts associated with reducing domestic water consumption, data is presented segmented and according to the economic characteristics of households (low, middle and high income).

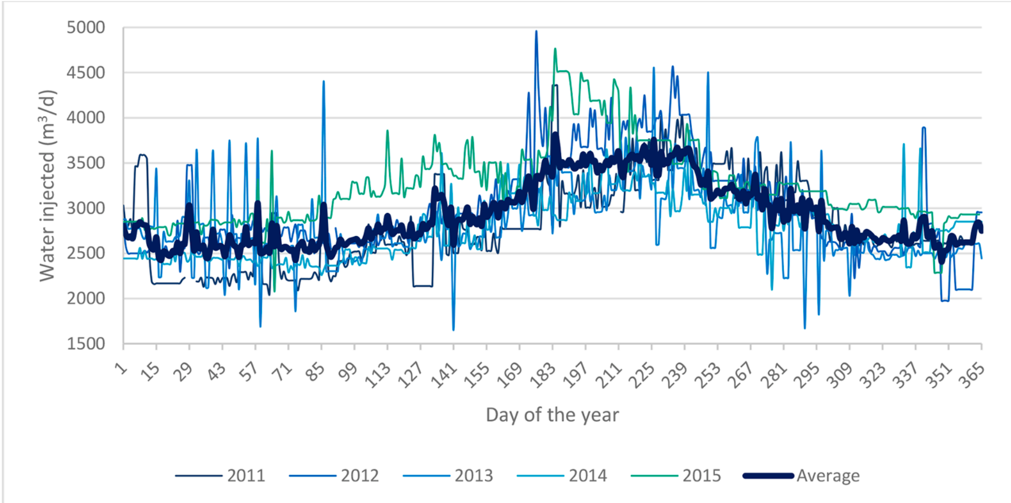


**Fig. 4.** Evolution of the domestic water injected into La Seu's network throughout the year.

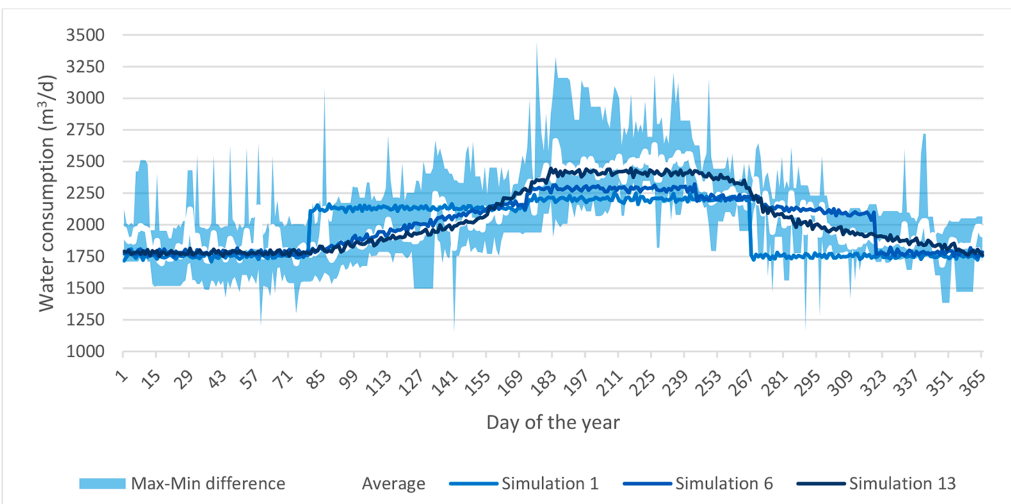


**Fig. 5.** Calibration iterations performed for water consumption in La Seu based on the agent-based model.

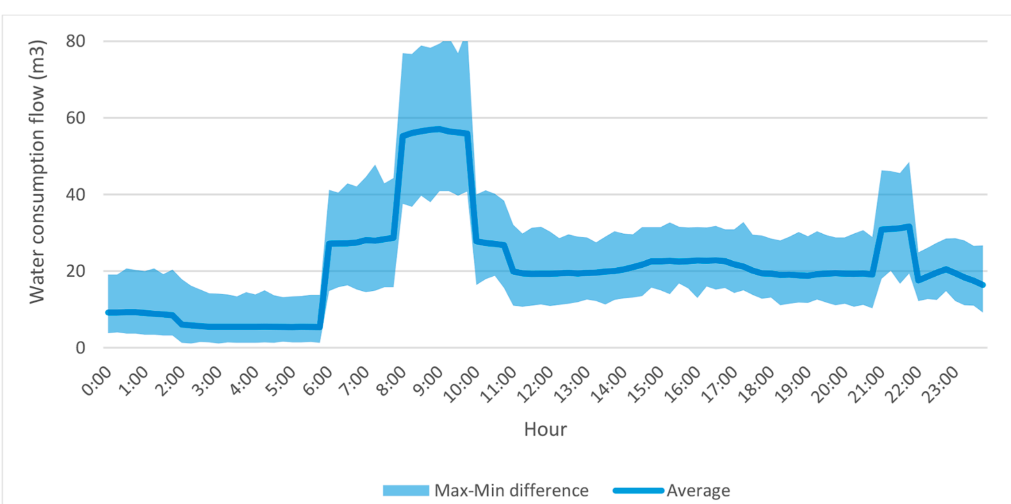


**Fig. 6.** Water consumption distribution through the day in La Seu.

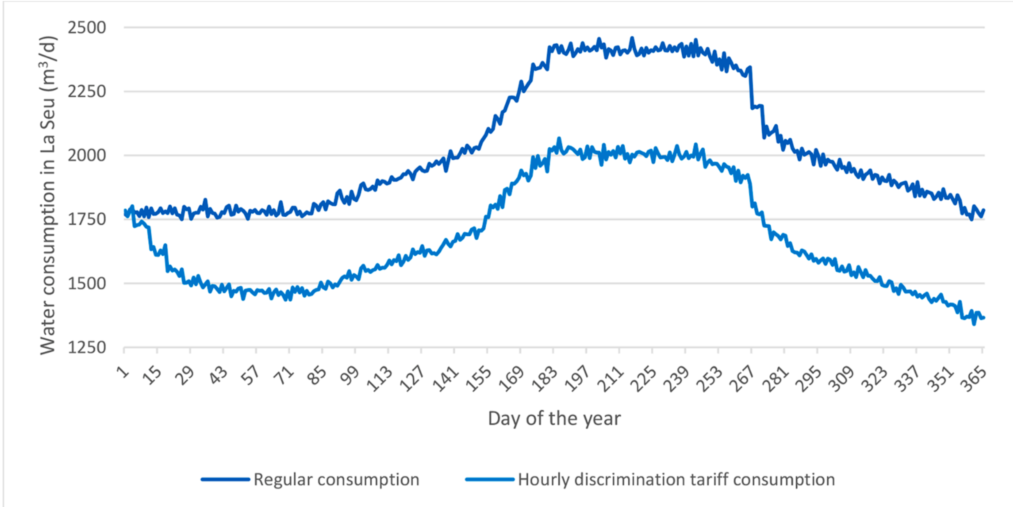


**Fig. 7.** Comparison of water consumption in La Seu with the different water tariffs approaches.

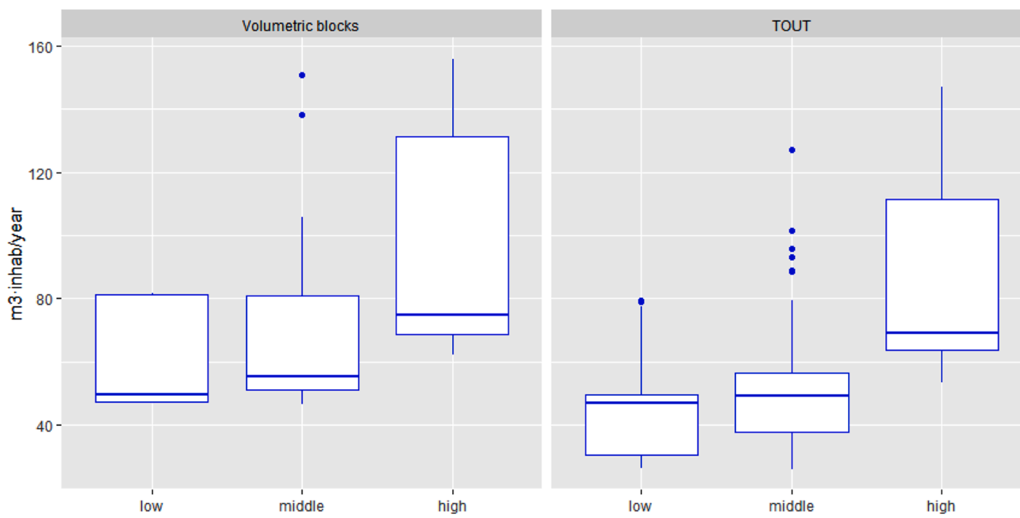


**Fig. 8.** Boxplot diagrams of water consumption based on the current water tariff (left) and the TOUT approach (right) for low-, middle- and high-income households in La Seu.

As shown by the boxplots in Fig. 8, the households with middle (€938 to 2,502/person/month) and low disposable income (up to €938/person/month) were the ones that most reduced their water consumption per person and year when the TOUT was applied. Table 9 compares this consumption decrease with the average money spent per person and year in households segmented by their income per capita. However, on average, households with a higher disposable income (more than €2,502/person/month) were those whose bills decreased the most.

The socio-cognitive factors implicated in the decision-making of the agents was also a key element of the analysis. As shown in Fig. 9, differences between households triggered by economic reasons and those with environmental ones were obvious.

Thus, we found an important difference between households whose actions are motivated by economic reasons, which reduced their consumption around 28% (31.9 % reduction for client households and 26.4 % for techno-solutionist) and those that do so because they want to save water (9.4 % reduction for committed households and 0.9 % for environmentalists). This difference highlights the limited capacity of water-demand management policies based solely on economic measures, in this case, pricing. The different socio-cognitive profiles of the population become a key variable when combining these types of measures with others that are more focused on environmental awareness, for example: different kinds of users can be targeted differently and encouraged to save water in accordance with their specific value profiles.

We also looked at how consumption would vary in the event of a housing expansion in la Seu. In this case, we supposed a 3.5% growth in the number of households (equivalent to 200 new medium-density housing units), attracting a new population with a disposable middle income and a techno-solutionist profile value. As expected, the results of the modelling process indicated that water consumption would increase in both cases. However, if TOUT was implemented, the increase in consumption was estimated at 3.9%, compared with 5.1% in the scenario when TOUT was not enforced. In this case, if the new inhabitants are techno-optimistic and triggered by economic reasons, TOUT helped to reduce the increase in water consumption caused by the growth of population.

## 5. Discussion

The simulations described in this article show that applying TOUT can indeed generate water savings, thus confirming the results of previous studies of dynamic pricing (Vasak et al., 2014; Rouge et al., 2018).


**Fig. 9.** Daily water consumption based on water tariff approaches for each profile value in La Seu.

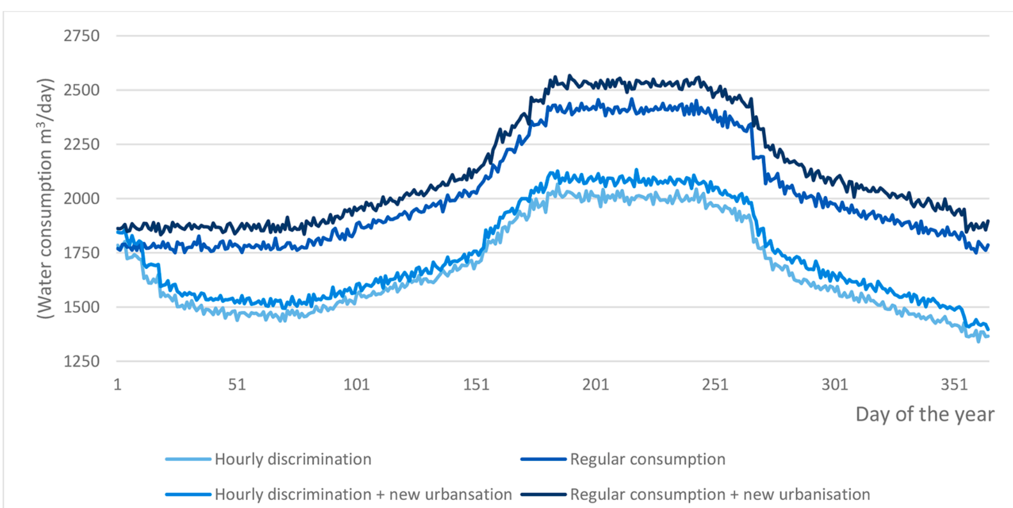


**Fig. 10.** Comparison of water consumption in the case of a new housing development with the different tariff approaches in La Seu.

**Table 7**
Reduction of consumption and frequency of use associated to practice changes (Perello-Moragues, 2020).

| Variable | Activity Hygiene (shower) | Dishwasher | Washing machine | Hygiene (handwash) |
|---|---|---|---|---|
| Consumption reduction after practice changes | -10 % | No changes | No changes | - 10 % |
| Standard frequency | 6 per week | 1 per person and week | 1 per person and week | 10 per day |
| Frequency after practice changes | No changes | (1 per person and week) – 1 if inhabitants > 1 | (1 per person and week) – 1 if inhabitants > 1 | 8 per day |

**Table 8**
Final prices for the Time-of-Use Tariff proposed.

| Time slots | Base of calculation | Price set in the model |
|---|---|---|
| Off-peak | 0.299 €/m$^3$ | 0.220 €/m$^3$ |
| Mid-range | 0.387 €/m$^3$ | 0.284 €/m$^3$ |
| Peak | 0.575 €/m$^3$ | 0.423 €/m$^3$ |

A 17.2% reduction in domestic consumption and a mitigation of the consumption rise caused by population growth would be thus achieved. Furthermore, personal values can make an important difference between water users.

Nevertheless, there are other consequences which need to be considered: most significantly, the measure puts pressure on households with less purchasing power, which are also those who produce the greatest reduction in consumption. This result contradicts other contributions in the literature, which conclude that TOUT would not affect

**Table 9**
Reduction in consumption and water expenses per person.

| | Disposable income per capita | | |
|---|---|---|---|
| | Low | Middle | High |
| **Regular consumption** (m3/person · year) | 58.94 | 63.68 | 93.15 |
| **TOUT applied** (m3/person · year) | 44.19 | 50.04 | 83.75 |
| **Reduction** | **25.0%** | **21.4%** | **10.4%** |
| **Regular consumption** (€/person · year) | 90.74 | 97.09 | 155.22 |
| **TOUT applied** (€/person · year) | 82.27 | 86.98 | 137.20 |
| **Reduction** | **9.3%** | **10.4%** | **11.9%** |

consumers economically (Rouge et al., 2018). In turn, wealthier houses witness a greater decrease in their water bills despite not being those who reduce their consumption the most. These results are due to the capacity of ABM to account for important variables such as changes in behaviours motivated by moral values. To our knowledge, this is first study to explore the feasibility of dynamic pricing of water via ABM. This allowed us a glimpse into the relation between socioeconomic and socio-cognitive profiles and water use practices. This is not only valuable from a scientific point of view, but also for policymaking, as it allows water-demand policies to address specific social groups and test their potential success.

Importantly, as the Water 4.0 paradigm advances towards increasing technologization of water management, our results confirm the risks of an indiscriminate application of digital technologies such as smart metering. As March et al. (2017) previously pointed out, smart meters could generate an 'overexposure' of citizens to consumption data which is, in our case, combined with a tariff change, and would lead those with lower income to excessively focus on reducing their water use. In turn, this could make them disregard other relevant household expenses, contributing to an increase in household economic distress.

With this in mind, water-demand policy interventions should not focus strictly on water savings through smart metering systems, as this may lead to unexpected and socially undesirable results whose negative effects, such as increasing inequality, may offset the benefits of water savings. Instead, it is crucial for these policies to consider all variables influencing water consumption when managing water demand, and also take into account all possible impacts produced by new management tools such as TOUT. Proper decision-support systems, relying on critical research are necessary to advise policy makers in charge of implementing these kinds of measures, thus helping to create and apply more holistic and socially driven cost-benefit analyses. In this sense, agent-based models can be useful tools for exploring cause-effect relationships associated with demand management policies.

Findings from this study evidence that innovative economic policy instruments such as TOUTs are useful tools to reduce water consumption in cities. Its implementation should be considered when water utilities undertake long term planning for water security. From a policy perspective, it is needed that water regulators explore the potential advantages of implementing TOUTs and promote them, especially in water scarcity areas. Nevertheless, results from this study also evidenced that households with large income are the ones that least reduced water consumption. Hence, educational campaigns are also needed to improve sustainability in domestic water use. This is of particular interest for our case study which focused on a small city. Bieretz (2020) reported that, unlike large cities, the nonprofit sector can help cities partially overcome municipal capacity challenges. Moreover, in the case of small cities, local organizations can play a relevant role to encourage communities to save water. Results from this study also revealed that TOUTs can reduce the household expenditures on domestic water service. This finding is very useful for policy makers (water regulators) in middle- and low-income countries where water affordability is still a barrier for guaranteeing the human right to water.

## 6. Conclusions

In the current context of water scarcity, it is essential to develop and implement effective and innovative approaches to manage domestic water demand. In this study, we were interested in TOUT as one of the most promising approaches to this. We not only quantified the potential water savings due to the implementation of a TOUT system but also linked the results with the social and economic profiles of households. To do so, we developed several scenarios using Agent-based Modelling.

Results for a case study of a town of 12,000 inhabitants in Northern Spain revealed that adopting a TOUT approach would reduce domestic water use by 17.2% in comparison to the current water tariff scheme based on increasing volumetric blocks. Higher reductions in water use (25%) occurred in low-income households, however, this water reduction translated in a mere 9.3% decrease in their water bills. The opposite occurred for high income households whose water consumption fell by 10.4% but their water bill decreased by 11.9%. These results showed that adopting a TOUT approach involves different economic impacts depending on the economic situation of the households involved. Therefore, complementary measures such as subsidies might be jointly implemented for the poorest households to guarantee sufficient water at affordable costs. To further evaluate the moral values behind saving water behaviours, four socio-cognitive profiles were modelled. Results demonstrated that households that save water for economic reasons by replacing water related fixtures were the largest water savers (31.9%). In contrast, environmentalist customers, (i.e., those saving water for environmental reasons) only saved 0.9% of their domestic water consumption by changing their habits. These findings highlight the importance of investigating the socio-cognitive profiles of households before implementing a TOUT approach. Moreover, reducing domestic water demand should not be based on a single measure only. Therefore, results from this study are relevant to define synergic and complementary measures to a TOUT system.

From a policy perspective, our results illustrate that water-demand policy interventions should not focus strictly on water savings through smart metering systems, as this may cause the unexpected results whose negative effects such as increasing social inequalities which, in turn, could offset the benefits of water savings. Instead, it is crucial for these policies to consider all the variables influencing water consumption when managing water demand and take into account all the possible impacts a new policy may have.

To the best of our knowledge, this is the first study that models the influence of socio-economic conditions of households on in water savings when a TOUT approach is implemented. Further studies using real data gathered by smart meters on the daily distribution of water consumption to calibrate the ABM are needed. Furthermore, deeper insights into value profiles to determine more specific profiles and their distributions would be necessary to better incorporate the socio-cognitive perspective of water consumption habits and practices. For instance, future research should analyse how different water management options affect consumers depending on gender. Another political issue to address is privacy and data protection. Trust in institutions and water providers having a strong socio-cognitive foundation is a key aspect in this respect (Figs. 2, 10, Tables 7, 8).

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2022.104118.

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