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A Hybrid Agent-Based Model for Estimating Residential Water Demand

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The global effort toward *sustainable development* has initiated a transition in water management. Water utility companies use water-pricing policies as an instrument for controlling residential water demand. To support policy makers in their decisions, the authors have developed DAWN, a hybrid model for evaluating water-pricing policies. DAWN integrates an agent-based social model for the consumer with conventional econometric models and simulates the residential water demand-supply chain, enabling the evaluation of different scenarios for policy making. An agent community is assigned to behave as water consumers, while econometric and social models are incorporated into them for estimating water consumption. DAWN's main advantage is that it supports social interaction between consumers, through an influence diffusion mechanism, implemented via inter-agent communication. Parameters affecting water consumption and associated with consumers' social behavior can be simulated with DAWN. Real-world results of DAWN's application for the evaluation of five water-pricing policies in Thessaloniki, Greece, are presented.

Keywords: Agent-based social simulation, residential water demand, multiagent systems, social influence, pricing policies

1. Introduction

Growing water demands, especially in the water supply sector, create a pressing need to develop alternative schemes for managing scarce water resources in an integrated manner. Contemporary urban water policies have to accommodate the renovation of infrastructure networks, the continuous demand for public services and facilities, new institutional arrangements, and the need for comprehensive management that enables public involvement and participation.

The reorientation of urban water management toward sustainability is closely related to the use of demand management practices to achieve an appropriate balance between capacity expansion and water conservation [1, 2]. This shift requires integration of engineering, environmental, and social and economic aspects of water supply planning and management. Water demand management can definitely lead to more effective and efficient decision making in water management [3, 4]. Economic incentives, water-pricing policies, public participation and awareness, and education and information strategies constitute today's powerful demand management tools, in the effort to balance supply and demand.

The traditional engineering-oriented approaches, with an emphasis on increasing water supplies, have led to the depletion of freshwater reserves, overexploitation, and underevaluation of water itself. Water utilities today need to combine "structural" and "nonstructural" approaches by taking into account the increasing per capita water use, the increasing population, urbanization, pollution, shortage of funds, and the growing competition for various uses of water. Policy decisions should take into consideration the preferences and interests of all groups being affected by policy actions.

In this article, we present DAWN, a hybrid model for estimating residential water demand. DAWN extends traditional econometric models by adding a social simulation layer to capture social responsiveness on water conservation policies and account for educational and information strategies. DAWN is an integrated model and tool that simulates social behavior, implemented as a multiagent system. The tool enables the user to explore how water policies may affect total demand, using a society of software agents, and it facilitates the design, creation, modification, and execution of different scenarios. In these scenarios, agents behave as water consumers, while econometric and social models are incorporated into them for estimating future consumptions. DAWN supports social interaction among consumers, by taking advantage of the ability of agents to communicate and exchange

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information. Thus, variables affecting water consumption and associated with consumers' social behavior can be included in DAWN scenarios. Following the description of the model, we present experimental results obtained from its application on aggregate, real-world data taken from the Thessaloniki Municipal Water Supply and Sewerage Authority (TMWSSA), in Greece.

2. Water Demand Management

2.1 Problem Formulation

In the literature, the terms *demand management* and *water conservation* are often used interchangeably. For example, demand management can be defined as the task of selecting specific actions among a range of available options for meeting target demands [5, 6]. On the other hand, water conservation was defined as "the socially beneficial reduction of water use or water loss" [7]. The term *socially beneficial* implies the trade-off between benefits and costs of water management actions. Accordingly, the main aims of demand management or water conservation are to encourage customers to make more efficient use of water. Examples of such demand management policies include the following:

- public campaigns to educate the consumers on how to modify water use habits in an effort to reduce water consumption,
- promotion of water-saving technologies,
- promotion of xeriscaping,
- adoption of marketplace pricing strategies to discourage inefficient uses of water,
- adoption of financial incentive programs to encourage efficient use of water.

Water utility policy makers are forced, in our days, to decide on whether to apply these policies without adequate feedback about implementation results. Such results can be obtained by evaluating procedures aiming on calculating the quantitative effects of a water demand management policy on water conservation. Evaluating a water demand management policy is an analytic activity that improves understanding of the consequences of the factors affecting water demand behavior and water use choices. The evaluation process aims on calculating future water demand changes due to the implementation of specific water demand management policies. The principle techniques of forecasting water demand are described in general terms in several works [8-16].

One of the factors that influences water demand and should be considered in the evaluation process is the social behavior concerning consumer decisions on water use. Conservation is a concept that people seem to generally embrace, but agreement over specific conservation practices can be far more difficult to achieve. Developing conservation programs requires community involvement in terms of both public participation and consumer education.

Many water utilities accept public campaign programs as tools for educating and informing consumers on how to modify their water use habits and subsequently reduce water consumption [17]. The results of such campaigns are difficult to evaluate: on one hand, public campaigns have a direct impact on consumers who participate in them. On the other hand, there is an indirect impact realized by the participants, who propagate the ideas of water conservation to their friends, fellows, acquaintances, neighbors, and so on. In this way, conservation signals spread throughout the community.

DAWN examines the propagation of water conservation signals in a simulation environment and can help water decision makers to understand the quantitative aspects of implementing an information and education policy toward controlling water demand.

2.2 Residential Water Demand Related to Social Aspects

The estimation of the residential water demand function has been an issue of growing significance among decision makers during the past decades. Economists have tried to shed some light on the effects of different types of economic techniques, estimating demand functions and calculating elasticities of the parameters that affect residential demand. To this end, many types of econometric models have been derived to relate water consumption to one or more variables such as water price, consumer income, household type or composition, temperature, rainfall, and others. However, little consideration is given on the social aspects of residential water demand.

Since the 1960s, water demand has been extensively studied, focusing mainly on estimating price effects on water consumption [18, 19]. However, there is no general consensus on a methodology for studying the impact of consumer education and information policies. These policies are widely used by the water industry for controlling water demand, with generally positive results [20, 21].

The population of well-informed consumers, as a result of a public campaign, is a social parameter usually modeled as a variable in the respective econometric models that captures a campaign's effects on water consumption during the implementation period. Elasticities for this variable reported in the literature vary between –0.04 and –0.19 (i.e., of a rather significant magnitude). Trying to interpret these numbers, one could argue that water conservation campaigns may have a sizable impact on total consumption. However, conventional econometrical models do not account for the social behavior of individual consumers; rather, they attempt to reflect the society as a whole in an aggregated form. The actual phenomenon involves the propagation of water conservation signals among individual consumers, who influence each other through their social relationships. Consumer behavior primitives and their effects on the propagation of water conservation signals are described in the following section.

2.3 Consumer Behavior and Propagation of Water Conservation

An education and information policy is typically implemented as a public campaign, through which the water utility communicates its messages to consumers using the mass media (e.g., television, newspapers, Internet, etc.). Considerable effort has been exerted in the fields of communication, marketing, and advertisement to identify how influence is propagated via media messages. The simplest influence model is the “stimulus-response” model, which suggests that mass media can influence people directly and uniformly by stimulating them with the appropriate messages to trigger a desired response [22].

This model considers people as passive receivers and was abandoned in the 1950s, after the study of Lazarsfeld, Berelson, and Gaudet [23] on the 1940 American presidential elections revealed that mass media signals do not affect the whole society directly; rather, they permeate through the grid of social connections. Specifically, Katz and Lazarsfeld [22] introduced a *two-step flow of communication model* to describe how influence spreads within a community. Response to media messages is mediated through social relationships, while the effectiveness of the messages is sharply limited by interpersonal relationships and social influence. Unlike the stimulus-response model, the two-step flow model stresses human agency. Media messages spread in a social network via contagious agents, called “opinion leaders,” who are respected by their followers. This theory views the opinion leader as a middleman between the impersonal mass media (advertiser) and the majority of the society (consumers) [24].

The two-step theory has been criticized because it implies that all opinion leaders are active recipients and that all followers are passive consumers of information [25]. More recent research has shown that the diffusion of ideas is not a simple two-step process. A multiple-step model is now more generally accepted [26] because it combines both direct and indirect means of social influence at multiple levels.

These models, though often criticized, remain relevant and fundamental to the diffusion of influence throughout a social community. They have led to the “diffusion of innovations model” [27, 28] and the “ideavirus model” [29]. Recently, the power of an individual to influence his or her social peers has been further accelerated through the Internet. Godin [29] describes how ideas propagate by creating an environment, such as the Web, in which they can fast replicate and spread.

In summary, the effectiveness of an education and information policy is highly related to individual behaviors. However, conventional water demand simulation methods and studies either ignore social behavior or treat it as a single parameter describing the society as a whole. To overcome this drawback and simulate individual social behavior, DAWN adopted an agent-based approach.

2.4 Agent-Based Social Simulations for Water Management

The past few years, agent-based social models have been successfully used in water management applications. Several interdisciplinary pioneering projects attempted to simulate the social aspects of water consumption in various domains. An example is the EOS project [30], which elaborated an agent-based model intervening for cooperative ecosystem management. In this approach, an agent community is employed to simulate the Fraser river watershed. Inter-agent communication is used to simulate stakeholder interaction and intervention strategies.

A second example is the SINUSE project, an agent-based approach for integrated management of a water table system. Agent models in SINUSE are used to represent interaction between a water table and its users while taking into account the social behavior of the farmers [31].

In the NEGOWAT project, a hybrid agent-based model addresses conflict resolution and negotiation for sustainable management at water catchments [32]. Specifically, cellular automata primitives, combined with inter-agent communication, have been used to simulate the connections within a water cycle, while agents have been used to represent farmers.

The SHADOC project evaluated irrigation practices in the Senegal River using agent-based modeling [33]. In this system, farmers and their water demands are simulated. A sequel of this model is the CATCHSHAPE multiagent system [34] that simulates both catchment features and farmer’s individual decisions.

The FIRMA (Freshwater Integrated Resource Management with Agents) project applied agent modeling for the simulation of natural, hydrological, social, and economical dimensions of water resources management at water basins [35]. In FIRMA, several agent-based models have been developed and used to represent consumers, suppliers, and government and their interaction at various levels of aggregation. FIRMA has been demonstrated in five areas across Europe. One pilot case [36, 37] explores the effects of precipitation and temperature on water availability in the Thames region of southern England, modeling the water demands of household consumers. Agents in the Thames prototype communicate with each other, sharing perspectives in the form of endorsements. In this approach, social engagement is simulated by agents “observing” each others’ behavior.

Finally, the Adour prototype was developed to simulate negotiations among water consumer groups of a catchment basin, using economical models. A formal computable bargaining model of multilateral negotiations is applied to the Adour Basin case, in the southwest of France, with seven aggregate players (three “farmers,” two “environmental lobbies,” the “water manager,” and the “taxpayer”) [38]. Adour agents participate in a negotiation process, bidding for available water.

2.5 The DAWN Approach

In DAWN, the water demand-supply cycle is simulated using an agent-based model. A community of agents serves as a sample of water consumers. This society reacts to the application of specific water-pricing policies, simulating the dynamic behavior of the actual consumers. Water consumer agents adopt an econometric model for estimating their consumption, augmented with a social activity model. Social interaction is realized through an *influence diffusion mechanism*, which simulates the propagation of water conservation signals within the consumer community, as a function of individual social relationships.

In the following section, the water demand-supply cycle and the agent-based model developed to simulate it are presented.

3. DAWN Agent-Based Model

3.1 The Water Demand-Supply Cycle in Urban Areas

The urban water demand-supply chain involves two main stakeholders. One is the water utility company, which supplies water to an urban area and puts the water-pricing policy into effect. The other is the area residents, who consume water and undertake its costs. The water-demand cycle involves a generic sequence of interactions between the two stakeholders. First, the water utility company initiates a pricing policy for managing water demand (among others). Then, the consumer society reacts to the selected pricing policy. Individual consumers reconsider their own water consumption with respect to water price, social influence, weather conditions, or other fixed parameters. Finally, the water utility revises its water-pricing policy in a timely fashion.

In DAWN, all actors involved are represented as agents. The water utility is represented by the *water supplier agent* (WSA), while the consumer society is represented by a community of *consumer agents* (CAs). Each CA represents a single consumer or a consumer group having common needs. Agents assume the responsibilities of actual stakeholders. A *meteorologist agent* (MOA) is added to supply the system with meteorological conditions. Finally, the *simulator agent* (SA) is used to moderate and synchronize the simulation procedure. SA is also responsible for capturing a user-defined scenario.

3.2 Agent Architecture

The generic architecture of DAWN is depicted in Figure 1. The user specifies a water management scenario and inputs it to the system through SA. SA facilitates the overall simulation procedure and appoints the user-specified parameters to all agents. The simulation procedure evolves in an iterative manner.

In each simulation epoch, WSA applies the water-pricing policy, and CAs react to it, reconsidering their individual consumption. A simulation epoch starts when the SA asks from the WSA the total consumption for the current time interval. The WSA contacts all CAs, informing them about the cost of water, consumed in the previous epoch. Each CA uses the econometric and social models to estimate its new consumption. Social activity between CAs is realized via agent messaging. Each CA reports its water consumption demands to the WSA, which calculates the total demand. The latter is passed to SA and presented to the user, marking the termination of the simulation epoch. The MOA agent is responsible for supplying meteorological conditions to all CAs. As weather conditions are community-wide, this information is passed to CAs through WSA. Note that the MOA agent intervenes in the process only if meteorological parameters are used in the model.

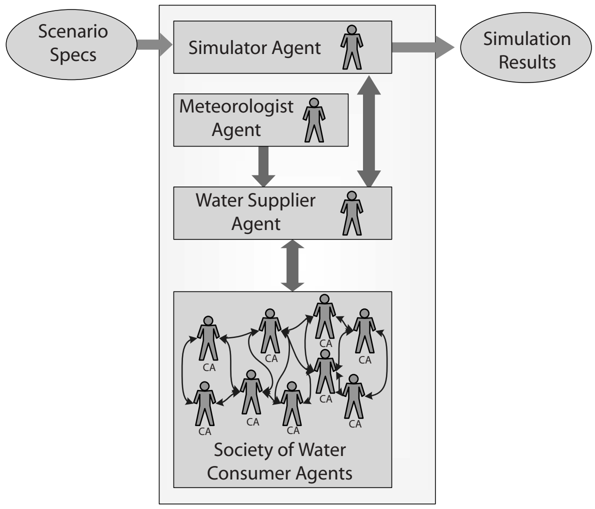

Figure 1. DAWN platform architecture

3.3 Agent Roles

The Gaia methodology for agent-oriented analysis and design [39] was used to specify in detail both the macro-level (societal) and the micro-level (internal) aspects of agent-based systems. Agent functionality in Gaia is specified using roles. A role can be viewed as an abstract description of an entity's expected function.

WSA realizes a single role, the WaterSupplier role, which comprises the main activities of the water utility, including querying the CAs for their consumption, calculating the total water consumption, cost-accounting water consumption, and reviewing water-pricing policy. The WaterSupplier role schema is shown in Figure 2. The WaterSupplier role permissions are (1) to read the pricing-policy parameters and the personal consumptions, (2) to write the total water consumed during each simulation epoch, and (3) to change the water-pricing policy.

Role Schema : WaterSupplier (WS)

Description :
Simulates the activities of the Water Supplier Agency. In each simulation cycle, WS asks all consumers for their water demands. Having collected all individuals consumption, calculates the respective costs and informs all CAs. It also calculates the total demand and potentially revises the water-pricing policy. The total consumption is presented to the user.

Protocols and Activities :
WaitStartStep, DecideWaterPrice, MetDataQuery, QueryConsumer, SendStepResults, CalculateStepTotalConsumption

Permissions :
Reads price-pricing model
Reads personal consumptions
Writes step total consumption
Changes price-pricing model

Responsibilities:
Liveness:
WS = (WaitStartStep . MetDataQuery . DecideWaterPrice . QueryConsumer $^{+}$.CalculateTotalConsumption .SendStepResults) $^{+}$
Safety:
True

Figure 2. The WaterSupplier role schema

Role Schema : WaterConsumer (WC)

Description :
Simulates the behavior of an individual consumer. Based on an econometric model calculates its personal water consumption during each simulation step.

Protocols and Activities :
ReceivePriceAndMetData, ContactNeighbour, ConsumeWater, DisplayStatus, SendPersonalConsumption

Permissions :
Reads neighbours list,demand curve parameters,step Id, water price, met data
Writes step personal consumption

Responsibilities:
Liveness:
WC = (ReceivePriceAndMetData . ContactNeighbour *. ConsumeWater . SendPersonalConsumption) $^{+}$ || DisplayStatus *
Safety:
personal water consumption > 0

Figure 3. The WaterConsumer role schema

The CA implements two roles: (1) the WaterConsumer role and (2) the NeighborConsumer role. The WaterConsumer role specifies a CA's functionality to consume water, while the NeighborConsumer role determines a CA's ability for social interaction. The WaterConsumer is able to calculate its personal consumption based on an econometric model. In each simulation step (epoch), it replies to WSA with its consumption. Each WaterConsumer consumption is influenced by its NeighborConsumer. The WaterConsumer role scheme is shown in Figure 3.

The NeighborConsumer role details a CA's behavior, acting as a neighbor of a WaterConsumer. Each NeighborConsumer propagates its social influence to WaterConsumer upon request. The social influence is communicated in the form of a "social weight." The social weights exchanged between consumers implement the *influence diffusion mechanism*. A NeighborConsumer is able to read a WaterConsumer's request, calculate its influence, and write

Role Schema : ConsumerNeighbour (CN)

Description :
Simulates the behavior of a neighbour consumer, participating in a social interaction process. It propagates its influence to all its neighbours, upon request. Its personal influence is represented as a "social weight".

Protocols and Activities :
CalculateWeights, ReplyNeighbour

Permissions :
Reads demand curve social parameters, step Id
Writes social parameters weights

Responsibilities:
Liveness:
CN = (CalculateWeights, ReplyNeighbour) $^{+}$
Safety:
neighbour E [myNeighbours List]

Figure 4. The NeighborConsumer role schema

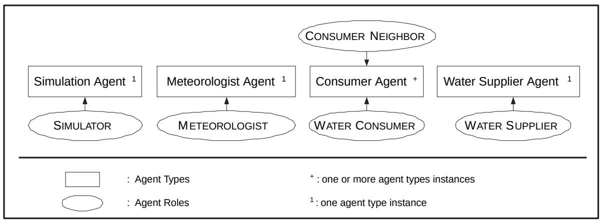

Figure 5. DAWN agent model

its response. The NeighborConsumer role schema is presented in Figure 4.

In a similar way, MOA realizes the Meteorologist role and SA the Simulator role.

The DAWN design process includes the creation of an agent model, which identifies the generic agent types involved and the agent instances that will be created from these types. The Gaia agent model for DAWN is depicted in Figure 5. Four generic agent types are defined (SA, WSA, CA, and MOA), and the appropriate roles are assigned. One instance of SA, WSA, and MOA is needed, while more than one CA instances are deployed to simulate the consumer society. Note that CA is simultaneously realizing two roles: the WaterConsumer and the NeighborConsumer.

3.4 Agent-Based Simulation Procedure

All agents, acting the roles specified in the previous section, interact with each other and implement the overall simulation procedure. The simulation is performed in eight steps, shown in Figure 6 and outlined below.

- Step 1: Scenario input and initialization. User specifies the scenario to be simulated. In particular, the water demand econometric model, the water-pricing policy, and the meteorological data are determined and incorporated in DAWN agents. Having all agents properly instantiated, the simulation iteration begins.

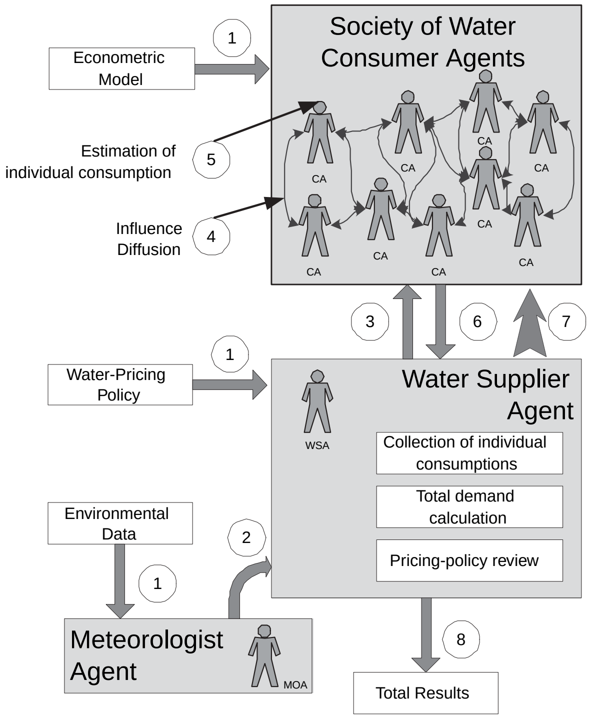

Figure 6. DAWN simulation procedure

- Step 2: MOA informs WSA on meteorological conditions.
- Step 3: Each CA is asked to determine its own water demand. CAs are also informed about the current meteorological conditions and water price.
- Step 4: Consumer agent community social activity. Consumer agents communicate with each other, realizing the *influence diffusion mechanism*.
- Step 5: Each individual consumer estimates its own water demand. This step takes into account the outcome of the social agent interaction.
- Step 6: Collection of all individual demands by the WSA and calculation of the total consumption.
- Step 7: WSA revises the water-pricing policy (if needed) and initiates the next simulation cycle (go to step 2).
- Step 8: When the iteration is over, the simulation results are presented to the user.

3.5 Implementation

Agents in the DAWN tool were developed in Java, using the Java Agent Development Environment (JADE) [40], and comply with the Foundation of Physical Intelligent Agents (FIPA) specifications [41]. DAWN implementation details are also discussed in Athanasiadis, Vartalas, and Mitkas [42].

The software agent interaction has been specified using the Agent Object Relationship Modeling Language (AORML) [43]. In Figure 7, the AORML external agent diagram is depicted. Each CA realizes two distinct roles, as mentioned earlier. To calculate its own demand, the CA communicates with its neighbors, asking for their *social weights*, while when asked for its social influence, it replies with the appropriate weight. Additional functional activities of all agents involved in DAWN are included in the diagram, along with the administrative functions of the platform, such as system parameters and user inputs. Note that the user is also considered.

So far, we have discussed in detail agent architecture, roles, functionality, and interactions. In the following section, we focus on the agent reasoning features. In particular, we present the hybrid model used in DAWN for estimating residential water demand. A generic econometric model has been extended with a social model developed in the form of the influence diffusion mechanism. Their integration into a hybrid model has been incorporated in CA.

4. Agent Reasoning

4.1 Econometric Model

In estimating water demand, studies have used a variety of methods and econometric models, depending on the nature and availability of data [44-46]. Water demand estimation is usually formed as a generic model of the form $C = f(P, Z)$, which relates water consumption C to some price measures P and other factors Z [8]. The residential water demand is estimated using the following generic equation:

$$C(i,t) = \alpha + \beta \boldsymbol{X}(i,t) + \gamma \boldsymbol{Z}(i) + \upsilon(i) + \epsilon(i,t) \quad (1)$$

where

- $C(i,t)$ is the water consumption in cubic meters for household i at time t;
- $\boldsymbol{X}(i,t)$ is the vector of price variables;
- $\boldsymbol{Z}(i)$ is a vector of community-specific variables;
- α, β, γ are coefficients to be estimated (elasticities);
- $\upsilon(i)$ is the unexpected water consumption regime or the unit-specific residual;
- $\epsilon(i,t)$ is the error term.

This econometric model is used separately by each CA to estimate its own water demands. Note that, in the form of equation (1), societal factors are represented as variables included in vector $\boldsymbol{Z}$.

4.2 Influence Diffusion Mechanism

In DAWN, the water consumer society is simulated as a set of CA. Each CA represents a single consumer or a consumer group having common needs. The flow of the communication model, described in brief in section 2.3, is simulated using CAs. Their communication simulates the

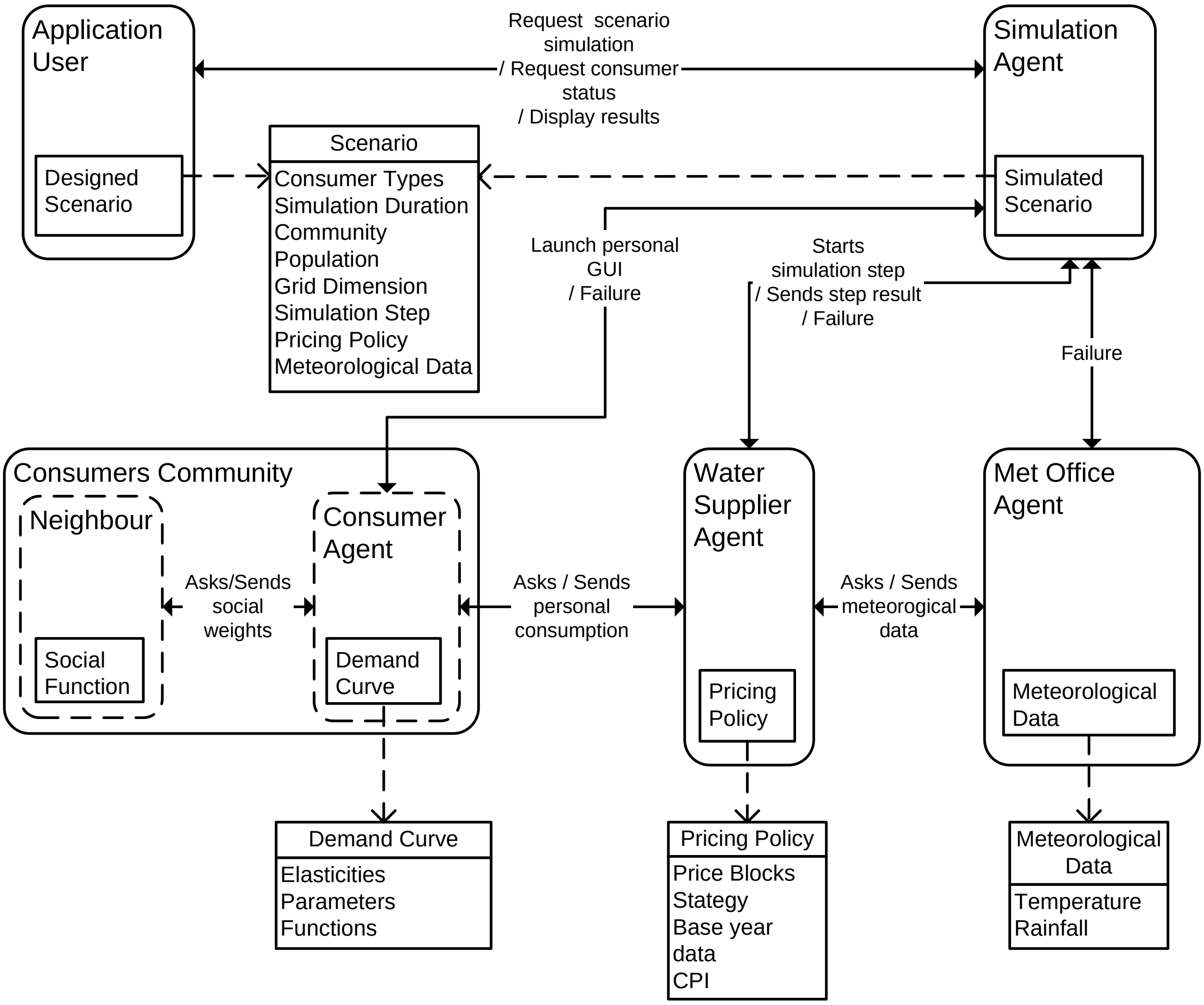

Figure 7. Agent Object Relationship Modeling Language (AORML) external agent diagram

social relationship among consumers, realized at multiple levels of influence. Specifically, there is both a direct effect of the campaign distributed uniformly to all affected consumers and an indirect effect realized by the diffusion of influence within the social web. CAs are situated on a square social grid. Each CA is determined by its position on the grid. So, a single CA is identified as $CA(x, y)$, where (x, y) are its coordinates on the grid. Social interaction between CAs is limited to a *neighborhood*, in analogy with the actual social interaction, which is not community-wide. Notice that the neighborhood is social and not geographical. Therefore, a CA's neighborhood is specified as the square area on the grid, whose center is the specific CA and its radius is defined by the *SightLimit* parameter sl. All agents residing in the neighborhood are supposed to be CA's *Neighbors*.

As an example, consider the 2-D grid of a side equal to 6, shown in Figure 8. Let the *SightLimit* parameter be $sl = 1$. For each CA, a neighborhood square of side 3 is defined. The neighborhood area of $CA(3, 3)$ is shown in Figure 8. The social model is realized in the neighborhood area, so $CA(3, 3)$ consumption is affected only by its two neighbors, $CA(2, 2)$ and $CA(2, 4)$.

The social interaction among agents is realized through the influence diffusion mechanism. Neighboring agents communicate their *social weights* (sw) that represent their power of persuasion. Social weights increase with the ability to persuade. Social influence has a cumulative effect;

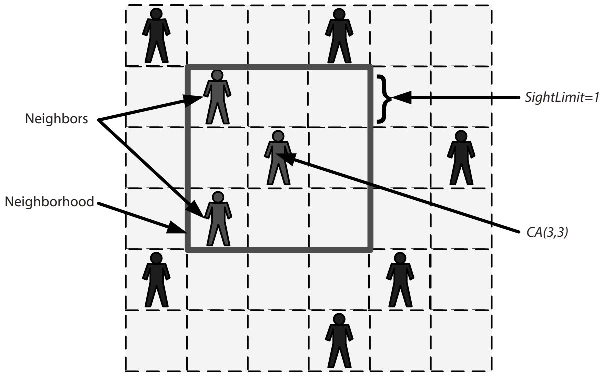

Figure 8. Consumer agent (CA) society distributed over a 2-D grid

thus, each CA sums all social weights received from its neighbors. This sum represents the total social influence that a CA experiences during each simulation epoch. A social variable S is determined by each CA_i at time interval t as

$$S(i,t) = f\left(\sum_N sw\right), \tag{2}$$

where sw are the social weights that consumer agent CA_i receives from its neighborhood N, and f is a diffraction function adjusting the sum of social weights. Function f is added to represent a consumer's ability to comprehend water conservation signals.

In accordance with the multiple-step communication flow model, opinion leaders are represented by CAs that communicate larger weights, which reflects their stronger ability for persuasion. Similarly, opinion followers are represented by agents with an amplifying diffraction function. In DAWN, the user can tailor these characteristics to specific consumer groups and, thus, define distinct CA types. Each type corresponds to a consumer group behaving in a similar way, thus sharing the same social model. In this way, dissimilar social behaviors can be simulated by distinct consumer-type agents.

4.3 The Hybrid Model

In DAWN's hybrid model, the social variables defined in equation (2) are incorporated into the generic econometric model of equation (1). The water consumption, in household i at time t, is determined as

$$C(i,t) = \alpha + \beta \boldsymbol{X}(i,t) + \gamma' \boldsymbol{Z'}(i) + \delta \boldsymbol{S}(i,t) + v(i) + \epsilon(i,t), \tag{3}$$

where $\boldsymbol{S}(i,t)$ is the vector of social variables and δ the corresponding coefficient to be estimated (elasticity). Note that $\boldsymbol{Z'}(i)$ is the original vector of community-specific variables (as defined in equation (1)), excluding social variables, which are now represented in $\boldsymbol{S}(i,t)$ and γ' the corresponding elasticities.

This hybrid model is used by all CAs to estimate their personal consumption for each time interval. In this way, the methodology used for water demand estimation, realized as an econometric model, and the social interaction agent-based methods are combined. The advantages of this approach are demonstrated in the following section, where we discuss the application of DAWN in the metropolitan area of Thessaloniki.

5. Experiments

5.1 The Case of the Metropolitan Area of Thessaloniki

The DAWN methodology has been used for estimating the water demand in the greater urban area of Thessaloniki, Greece. The metropolitan area of Thessaloniki comprises more than one million consumers. Aggregate data were obtained from TMWSSA.

Prior studies were conducted with a cubic econometric model. A residential water demand model was used to accommodate different price elasticity estimates for different volumes of water demand [47, 48]. Specifically, that conventional econometric model considered jointly (1) historical consumption data from TMWSSA records, (2) consumer questionnaire data, and (3) meteorological data.

Data on household characteristics and community-specific variables were collected by a field survey conducted in 1356 households through a questionnaire survey using cluster sampling in the 17 municipalities of the metropolitan area. Survey data were matched with TMWSSA records (price structure, changes in pricing policy, water consumption, public awareness, and information). The data cover the period from January 1994 until the first 4 months of 2000 (19 time-series observations in total).

This questionnaire survey, reported in Kolokytha, Mylopoulos, and Mentes [29], investigated, among others, the reliability of water utility services and infrastructure, the societal acceptability of various demand options, the consumers' willingness to pay for urban water, and the level of public awareness.

Also, monthly climatic data were collected from the Institute of Climatology and Meteorology of the Aristotle University of Thessaloniki.

In total, there were 25,764 pooled time-series and cross-section observations. To derive direct price elasticity estimates of water demand, a log transformation of equation (1) was used. The independent variables involved, along with their respected elasticities, and their standard deviations, are summarized in Table 1. The econometric model is detailed in Mylopoulos, Mentes, and Theodossiou [48].

In the conventional econometric model, a variable was introduced in the demand function to capture the

Table 1. Variables, elasticities, and their standard deviations

Variable		Elasticity	Standard Deviation
Marginal price	*MP*	–0.340	0.0851
Marginal price squared	MP^2	–0.308	0.0654
Marginal price cubed	MP^3	0.158	0.0843
Temperature	*TEM*	0.100	0.0975
Rainfall	*RNF*	–0.015	0.0127
Well-informed consumers	*WIC*	–0.368	0.1253
Family income	*INC*	0.351	0.1894
Having many children	*CHI*	0.194	0.0631
Car washing	*CAR*	0.055	0.0322
Watering plants	*W*	0.128	0.0583
Cleaning balconies	*B*	0.043	0.0191
Cleaning pavements	*P*	0.032	0.0220
Household residents	*RES*	0.026	0.0075

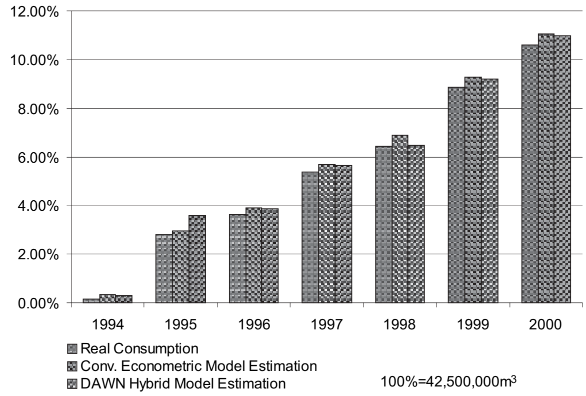

Figure 9. Comparative results for the calibration period: Annual percentage increase of total water consumption

well-educated and well-informed consumers—namely, the water utility employees. It was found [48] that although these employees are not charged for their water consumption, they have a positive attitude toward water conservation. This can be interpreted as a tendency of individuals, who are well informed about water problems, to save water even when there is no economic incentive to do so. In addition, one of the main conclusions of the field survey on consumer households was that the great majority of the respondents are willing to get informed about water issues through the water agency's special editions, local mass media, and so on. Based on these two findings, the elasticity of well-educated and well-informed consumers was assigned to a social variable, *WIC*, in the form of S in equation (2), capturing social interaction among consumers. In this way, the contemporary econometric model was extended. The hybrid DAWN model, including the *WIC* social variable, was then calibrated as described in the following section.

5.2 DAWN Model Calibration

The parameters of the hybrid DAWN model were defined consistent with the real-world data described above. The hybrid model was applied on available data covering the period 1994-2000, in order to be calibrated. The results of the calibrated hybrid DAWN model are shown in Figure 9 in comparison with the actual consumption and the consumption predicted by the conventional econometric model. Prior studies in the area of Thessaloniki had used the conventional econometric model for forecasting demand for the specific period [49].

Using the conventional approach, the social variable of well-informed consumers (*WIC*) was included in an aggregate form (i.e., an average value was considered for the whole society) as a fixed variable-type Z in equation (1). It was also assumed that the value of the well-informed consumers variable increases by an average of 6% in 3 years, meaning that it follows the relation $WIC(t) = \frac{0.06}{36}t + WIC(t_0)$, where t is in months. Results achieved with the conventional model are presented in Figure 9.

Using DAWN, the *WIC* variable was used through the social diffusion model. During the simulated period, no public campaign was implemented; thus, one could imply that there were no external stimuli from the mass media to trigger social interactions. However, people continued to have social interactions, albeit at a *low level*, affecting their consumption. This behavior was projected in DAWN by having 100 CAs randomly distributed in a 12×12 square grid. The social weights communicated by CAs were set to be equal to the factor $\frac{0.06}{36} = sw$, while the diffraction function was supposed to be linear. These results are also shown in Figure 9.

The estimation performance of the DAWN model was satisfactory compared with both the actual figures and the conventional approach. Figure 9 shows the percentage increase of total consumption. DAWN model managed to estimate accurately the water demands for the calibration period. The calibrated model was subsequently used to estimate water demand in the region of Thessaloniki, for the years 2004 to 2010.

5.3 DAWN Scenarios

The hybrid DAWN model was used to evaluate five different water-pricing policies for the period 2004-2010. DAWN simulation settings remained those of the calibrated model (i.e., a community of 100 consumers has been simulated, for each policy evaluation). The five pricing policies are the following:

The pricing policy is reviewed yearly, while

- Scenario A: Water price is adjusted to the real price, without the implementation of any education or information policy.

1. This means that the water tariff increases by the inflation rate.

- Scenario B: Water price is increased by 5%, without the implementation of any education or information policy.
- Scenario C: Water price is increased by 7.5%, without the implementation of any education or information policy.
- Scenario D: Water price is adjusted to the real price, with the implementation of an education or information policy of medium scale.
- Scenario E: Water price is adjusted to the real price, with the implementation of an education or information policy of major scale.

Annual inflation rates in Greece are expected to remain well below 5% for the next 5 to 10 years.

Consumer agents were clustered in four types, with respect to their abilities to *promote* and *comprehend* water conservation signals. These groups are presented in Table 2. In our experiments, only 10% of the population is considered to be directly affected by the water conservation policy. Type A consumers act as promoters or opinion leaders, and they represent people willing to actively propagate water conservation signals in their social communications. Specifically, the implementation of an education and information policy is expected to stimulate environmentally aware people, who will not only decrease their own consumption but also influence their neighbors. Opinion leaders will promote water conservation signals, via the influence diffusion mechanism, while they behave as early adopters of the campaign. Note that since they are supposed to be environmentally aware, their ability to further lower their water consumption is generally limited.

A fraction (20%) of the consumers is insensitive to social issues and generally indifferent to public awareness campaigns. These socially apathetic consumers (type B) can neither promote nor comprehend water conservation signals and have a negative attitude about conservation.

The remaining 70% of the population is indirectly affected, as they are supposed to be socially sensitive and act as opinion followers (i.e., they are influenced by the campaign through their social relations with opinion leaders). We have divided this group of consumers in two types. In type C (30%), we clustered all those people who seem willing to revise their water demands (i.e., they behave as opinion seekers). They are people who are aware about water conservation but still need some encouragement to change their water consumption habits. Opinion seekers are characterized by their ability to easily comprehend water conservation signals. The last 40% (type D) are the average consumers introduced in the calibration model. They are the opinion receivers, who adopt an “effortless” behavior about water conservation. Their attitude is passive, as they need considerable pressure by their social contacts to start changing their water demand habits.

The distribution of consumer types was based on the conclusions of the questionnaire [47]. For example, the majority of the responders said that they would be perceptive to a campaign, while the portion of the negativists remained at 20%. Another question of the questionnaire concerned the self-classification of the sample according to their consuming attitude. About one-third of the respondents claimed that they would be ready to reduce their consumption attitude, without affecting their quality of life. As a consequence, we inferred that this group of people is willing to conserve water but still needs some encouragement to change their water consumption behavior. Thus, the population of the opinion seekers (type C) was set to 30%.

Table 2. Consumer types

Consumer Type	Population (%)	Ability to Promote	Consumption Reduction
A: Opinion leaders	10	High	Low
B: Socially apathetic	20	None	None
C: Opinion seekers	30	Low	High
D: Opinion receivers	40	Low	Low

Following this procedure, we tried to map the actual society of consumers to the 2-D social grid of DAWN agents. Consumer ability to promote water conservation signals within a communication flow model is mapped using the CAs’ ability to influence their neighbors by communicating social weights. Consumer ability to change their water demand habits is mapped using the diffraction function. These agent abilities are realized by the influence diffusion mechanism presented in section 4.2. When a CA is characterized with high ability to promote conservation signals, it communicates to its neighbors high values of social weights (sw). When a CA is characterized by a high ability to comprehend conservation signals, the diffraction function f amplifies the influence collected by its neighbors. The actual values of these parameters were set with respect to the calibrated model. High ability to promote corresponds to the distribution of social weights at a magnitude twice as high as that of consumers with low ability to promote. The same is valid for the ability to comprehend and the diffraction function.

5.4 Results

Having specified the CA types, DAWN was used to evaluate the five scenarios by simulating the water demand-supply cycle as an iterative process. Each simulation epoch was supposed to be 1 month. The quantitative estimations obtained by DAWN for the period 2004-2010 are shown in Figure 10 in the form of consumption per capita and in Figure 11 in the form of yearly total consumption. In the comparative diagram of Figure 12, the proportional reduction of per capita water consumption is illustrated, with scenario A being the baseline scenario. Price in scenarios B and C and information and education campaigns

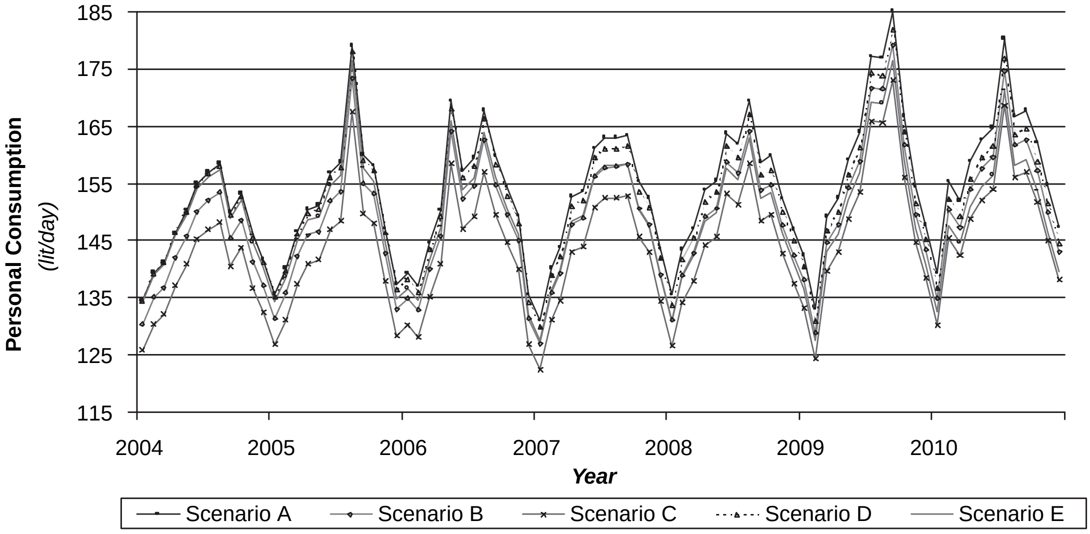

Figure 10. Consumption per capita

in scenarios D through E have been used to control water demands. However, as the total population of the city is expected to grow, the yearly total consumption is expected to grow under all scenarios, as shown in Figure 11. Also, the implementation of information and education campaigns (scenarios D-E) seems to require more time for the people to respond, but the medium-term results are more intense.

Results obtained with DAWN, without the implementation of any education or information policy (i.e., the social model was not applied), are similar to those of prior studies using contemporary econometric models. The added value of DAWN is that it supports scenarios implementing an education and information policy. A first reading of the quantitative results drives toward two conclusions: (1) the implementation of an education and information policy of medium scale, in conjunction with adjusting water prices by the inflation (scenario D), has similar effects with increasing water price by 5% (scenario B), and (2) the effects of an education and information policy are proliferating over time. Also, a major conservation policy may yield water savings of more than 5% of total demands, as shown in Figure 11.

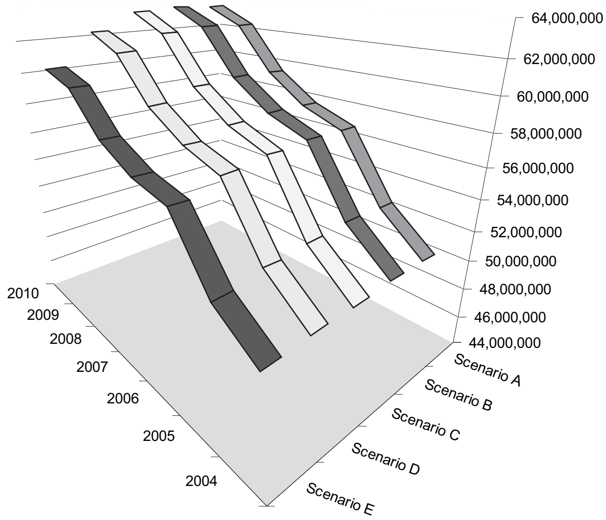

Figure 11. Yearly total consumption

6. Conclusion

In this article, a methodology for more accurate water demand estimation was presented. DAWN was inspired by the successful developments of agent-based social simulations for urban water management, discussed in section 2.4, as the Thames [36, 37] and Adour [38] models. However, there are clear differences between them. Economical models in Adour are used to realize the bargaining model between water users, while in DAWN, an econometric model widely adopted by the water management community has been incorporated for estimating an individual's water consumption. In contrast to the Thames model, social engagement between consumer agents is not realized by behavioral observation; rather, it is performed through an influence adaptation mechanism, and the social phenomenon evolves in a social grid, rather than a geographical one adopted in Thames. DAWN takes a step ahead in the estimation models applied in the residential water demand sector.

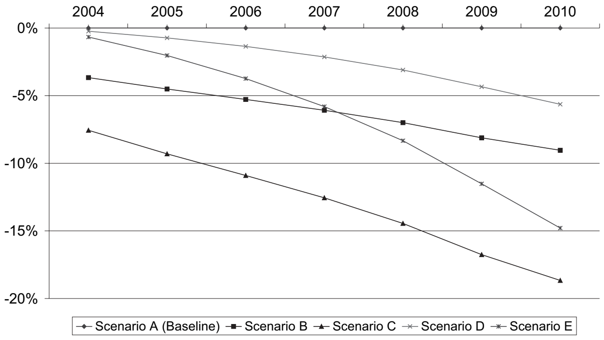

Figure 12. Comparative estimation of the per capita reduction

The water demand estimation model in DAWN combines a contemporary econometric model with an agent-based social model. The hybrid model is realized as a multiagent system presented in this article. All agents involved in the simulation procedure have been specified in detail and were implemented in Java using software agents. Also, the influence diffusion mechanism has been introduced to simulate the social interaction among water consumers.

The model has been applied in the metropolitan region of Thessaloniki, for estimating future water demands. It was parameterized with respect to prior field studies in the same region. DAWN's integrated approach was used to evaluate five water-pricing scenarios and obtain quantitative estimations of future needs. The use of DAWN has assisted water decision makers to understand the quantitative properties of implementing an information and education policy in the direction of controlling water demand. The results were presented to policy makers at TMWASSA, who have requested a larger scale simulation already in the planning.

7. Acknowledgments

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