Agents as a Decision Support Tool in Environmental Processes: The State of the Art

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Agents as a Decision Support Tool in Environmental Processes: The State of the Art

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Abstract. Agent-based systems have become an important area of research since the 1990s. They have been applied to a range of domains that are intrinsically complex. Among these, environmental problems are of special concern, given their ample affectation to our societies and everyday quality of life. This report provides a review of agent-based systems applied to environmental problems of diverse nature. The usefulness of Multi-Agent Systems (MAS) to model complex systems that embed multiple and dynamic interactions, such as in environmental processes, is revealed.

Keywords. Agent-Based Modeling, Environmental Processes, Multi-Agent Systems, Natural-Resources Management.

1. Introduction

The constituent parts of the environment (*i.e.* different life forms, energy and material resources, and the atmosphere) interact with each other. As an example, changes in biosphere composition affect the atmosphere composition. For our concern, more important are the effects of human activity on the environment, and the consequences of these affects on human well-being.

All environmental problems are essentially related to the use and distribution of resources, affecting water, air and soil quantity and quality. Environmental problems can be categorized in a number of ways. However, *resources overexploitation* and *environmental pollution* is amongst the most serious of existing category of problems. The growth of population and economic wealth, together with the increase of several processes, such as urbanisation and industrialization, has lead to a high consumption of natural resources and consequently, negative effects on the sustainability of the environmental quality have risen.

On the one hand, some forms of pollution can disrupt complex biogeochemical cycles and on the other, pollution brings significant social and economic consequences. As follows, we portray briefly the three main categories of environmental pollution: water, air and soil pollution. Their related problems are of special concern.

Water pollution (in oceans, rivers, lakes, aquifers, *etc.*) is any chemical, physical or biological change in the quality of water that has a harmful effect on any living organism that drinks or uses or lives (in) it. Water pollution sources are often classified as point and non point sources. Point sources discharge pollutants at specific locations through pipelines or sewers into the water bodies (*e.g.* industries, sewage treatment plants, underground mines, oil wells, oil tankers, *etc.*). Non point sources are sources that cannot be traced to a single site of discharge (*e.g.* acid deposition from the air, traffic, pollutants that are spread through rivers, agriculture runoff, *etc.*).

Air pollution supposes the introduction into the atmosphere of chemicals, particulate matter, or biological materials that cause harm or discomfort to humans or other living organisms, and/or damages the environment. Although air pollution is often identified with major stationary sources (*i.e.* industries), the greatest source of emissions is produced by mobile sources (*i.e.* automobiles).

Finally, soil pollution is caused by the presence of man-made chemicals and other alteration in the natural soil environment. This type of pollution commonly is originated due to the application of pesticides, the percolation of contaminated surface water to subsurface strata, oil and fuel dumping, leaching of wastes from landfills or direct discharge of industrial wastes to the soil, *etc.* It affects directly the habitat in which biodiversity is embedded and any other natural and/or human land uses.

Environments have some capacity to absorb and neutralize many substances (resilience), so a distinction is often made between *pollution*, involving harmful effects, and *contamination*, the presence of a substance in the environment below the damage threshold. This distinction is very clear in theory, but sometimes very difficult to establish in practice. In fact, environmental problems at all scales - from the merely local to those with long-term global significance - raise certain fundamental issues which make their resolution difficult and controversial. Some recurrent issues, many of them interrelated, include the following:

- Environmental problems are *multidisciplinary* by nature. As a consequence, in most environmental management situations, a single expert who can solve the problem entirely does not exist. Different opinions about the causes, consequences and possible solutions for the problem exist. Thus, conflict is inherent when trying to solve environmental problems due to the multiplicity of views and interests involved.
- Environmental problems are often characterized by great *uncertainty*. The complexity of environmental systems means that our understanding of the

human impact upon it is very partial, and accurate prediction is often impossible. Collected environmental information is often imprecise, uncertain or erroneous. As knowledge advances, uncertainties are reduced, but they can rarely be eliminated.

- Environmental problems involve strong *spatial* and *temporal distribution*. The multiplicity of scales has been traditionally associated with distinct spatial scales (*i.e.* local, regional, global), each associated with specific timescales. The irregular distribution of environmental problems in time and space make difficult to well define the interactions among these scales.
- Environmental problems are hard to model and understand. Environmental problems, as well as environmental systems, are *dynamic* in nature, and therefore deep models of their behavior are difficult to reproduce.

The experts' reasoning about environmental problems and decision making about suitable solutions is understood as manipulating high amount of specific data, mathematical models of the real situation, simulations, *etc.* In case of *inaccessibility*, *incompleteness*, or *incorrectness* of data as well as in other situations with high degree of uncertainty, experts still are able to make decisions. However they need to understand, in a limited time, chemical, physical and biological processes in relation to socioeconomic conditions and applicable legislative framework. The high complexity of environmental problems, characterized by the aforementioned most frequent issues, has lead to the use of knowledge-based decision support tools in decision processes.

2. Environmental Decision Support Tools and Agent-Based Paradigm

Over the last few decades, mathematical/statistical models, numerical algorithms and computer simulations models have been used as an appropriate means to gain insight into environmental management problems and provide useful information to decision makers. To this end, a wide set of scientific techniques has been applied to environmental management problems for a long time and with good results. The effort to integrate new tools to deal with more complex systems has led to the development of so-called Environmental Decision Support Systems (EDSSs) ([31], [71]).

EDSSs have generated high expectations as tools to tackle high complex problems. The range of environmental problems to which EDSSs have been applied is wide and varied, with water management at or near the top, followed by aspects of risk assessment and forest management. Equally varied are the tasks to which EDSSs have been applied, ranging from monitoring and data storage to prediction, decision analysis, control planning, remediation, management, and communication with society. Environmental issues belong to a set of critical domains where wrong management decisions may have disastrous social, economic and ecological consequences. Decision-making performed by EDSSs should be collaborative, not adversarial, and decision makers must inform and involve those who must live with the decisions. EDSS should be not only an efficient mechanism to find an optimal or sub-optimal solution, given any set of whimsical preferences, but also a mechanism to make the entire process more open and transparent.

According to Fox and Das [27], a decision support system is a computer system that assists decision makers in choosing between alternative beliefs or actions by applying knowledge about the decision domain to arrive at recommendations for the various options. It incorporates an explicit decision procedure based on a set of theoretical principles that justify the "rationality" of this procedure.

Intelligent Environmental Decision Support Systems (IEDSS) are intelligent information systems that reduce the time in which decisions are made in an environmental domain, and improve the consistency and quality of those decisions, by integrating several types of information and knowledge [67].

IEDSSs are tools designed to cope with the multidisciplinary nature and high complexity of environmental problems. The main advantages of using IEDSS to solve environmental problems rely on [71]:

1. The ability to acquire, represent and structure the knowledge.
2. The possibility to separate the data from the models.
3. The ability to deal with spatial data (incorporating GIS tools, for example).
4. The ability to provide expert knowledge (incorporating specific knowledge bases).
5. The ability to be used effectively for diagnosis, planning, management and optimization.
6. The ability to assist the user during problem formulation and selecting the solution methods.

Thus IEDSSs could be defined as systems using a combination of models, analytical techniques, and information retrieval to help develop and evaluate appropriate alternatives ([77], [1], [78]); and such systems focus on strategic decisions and not operational ones. More specifically, decision support systems should contribute to reducing the uncertainty faced by managers when they need to make decisions regarding future options [30]. Distributed decision making suits problems where the complexity prevents an individual decision maker from conceptualizing, or otherwise dealing with the entire problem ([14], [16]).

The use of AI tools and models provides direct access to expertise, and their flexibility makes them capable of supporting learning and decision making processes [67]. This confers on IEDSSs the ability to confront complex problems in which the experience of experts provides valuable help for finding a solution to the problem. It also provides ways to accelerate identification of the problem and to focus the attention of decision-makers on its evaluation.

Most developed IEDSS are based on traditional artificial intelligence approaches. These approaches are clearly bounded in the way and reliability they can solve the aforementioned environmental issues. However, since the 90s, the agent-based paradigm has emerged as a potential tool to deal with the interaction of humans and ecosystems, citizens and stakeholders, as they are tools designed to cope with the multidisciplinary and distributed nature and high complexity of environmental problems. An intelligent agent could be defined as any autonomous entity that is capable of perceiving its environment and carrying out goal-directed action ([72], [86]). *Agent-based approaches* have introduced both a powerful metaphor and a group of technologies in the field of IEDSS, giving support to the management of environmental problems, mainly of those concerning the management of renewable resources (*e.g.* water management, biodiversity management, forest management, erosion and soil management, *etc.*). These problems represent typical dynamic and unpredictable multi-agent domains, where flexible autonomous action is required to adapt to changing conditions. The need to cope with dynamic and emergent situations requires application components to interact in more flexible ways. The characterization in terms of *agents* has proven to be a most natural abstraction to many real world problems, having convinced researchers and developers in a wide variety of domains (*e.g.* [59], [35], [4]) of the great potential of multi-agent solutions.

Multi-Agent Systems (MAS) are built describing numerous agents with a different degree of complexity, according the information and knowledge available. The complexity and degree of knowledge can be improved without the necessity to modify all the system (they are intended to be systems with high modularity and scalability). The system can be extended with the addition of new types of agents and adding new capabilities into the implicit ontology without a central control, by just publishing it as part of agent self-description [43].

Briefly, for *modular*, *decentralized*, *changeable*, *ill-structured* and *complex system*, software intelligent agents are really appropriate [61].

3. State of the Art of Agent-based Applications in Environmental Management

In [4] a review of various published applications are considered. The review is done from both agent-oriented software modeling and implementation perspectives. Athanasiadis remarks that the applications can use agent-based approaches and methods, either as a metaphor for software design or as an abstraction for software development. The applications (an overall of 23 dating from 1996 to 2004) are grouped in three categories to ease their presentation:

1. *Environmental information and data management* (Environmental Data Management Systems (EDMSs)). In most of environmental problems available data and information is characterized by the attributes mentioned in §1: uncertain, imprecise, incorrect, and spatially distributed. EDMSs are needed to tackle with this kind of information. EDMSs are aimed at managing, integrating or distributing environmental data.

2. *Decision support in environmental problems* (Environmental Decision Support Systems (EDSSs)). Most of the applications in this category use agent methodologies and technologies in a way to make the decision-making distributed and shared between the different experts and stakeholders involved in specific environmental problems.
3. *Simulation of environmental or ecological systems and processes* (Environmental Simulation Systems (ESSs)). Agent-based ESSs use agents as the structuring blocks for modeling processes and interactions. The growing interest in this technique is due to the possibility to incorporate almost directly and intuitively the behavior observed in the real world by means of a computational model.

Then, the applications are reported with its main tasks and objectives, the application field, related technologies and principal agent types involved. Next, they are evaluated in terms of their level of software design and development (from low to upper level design, and from objects to agent-platforms implementation, respectively). In Tables 1–5 (see pp.22–26) we update and rationalize the available agent-based applications in environmental management following partially the criteria used in [4], and continuing the revision from 2005. The classification of applications in one of the three aforementioned categories (*i.e.* EMS, EDSS and ESS) is not always obvious, since the boundaries between the three categories are intertwined and not always clearly discriminated. The overview of applications is presented chronologically ordered (from the oldest to the newest published references). Four columns have been added to better describe the systems reviewed. These columns make reference to:

Software design: From this aspect it is possible to analyze the use of agent-related technologies in software design and modeling. That is, how the agent's concept is used. According to [4] four levels of agent's design complexity can be distinguished:
- (1) At the lowest level there are systems that use some agent-alike *entities*.
- (2) In the second level the systems are modeled using agents (a model), typically involving UML design.
- (3) The third level involves agents for software specification, that is the use of BDI [69], LORA [87] or similar techniques.
- (4) In the fourth level the systems adopt a sophisticated agent-oriented software design process as Gaia [88] or Tropos [29].

Software development: From the point of view of software implementation four levels of agent-related technologies can be identified:
- (A) Implementation with objects.
- (B) Implementation with software agents, typically dealing with FIPA standards (http://www.fipa.org).
- (C) Implementation using available agent platforms such as JADE, ZEUS, JACK, *etc.*.
- (D) Implementation using an own platform.

Implementation: In this column we refer to the system's implementation phase or stage. That is, if the reviewed systems are in the design phase or at the beginning of the development, partially or fully implemented, in progress, *etc.* Somehow it completes the information give in the 'software development' column.

Validation: In this column information on whether the agent-based system has been or not tested is given. In computer modeling and simulation, validation is the process of determining the degree to which a model or simulation is an accurate representation of real world from the perspective of the intended uses of the model or simulation.

As follows, a brief explanation of each of the applications reviewed is provided. In this review we have only considered those applications related to environmental management issues; other domains such as economics ([20], [34], [80]), telecommunications ([85], [15]), healthcare ([33], [55], [3]), manufacturing ([62], [17]), military support [82], *etc.* sustain the suitability of agent-based applications in complex domains. However, although the intention is to present only those agent-based applications related environmental management issues, some of the applications are either not developed exclusively with agents or they do not deal solely with environmental management applications.

The **DAI-DEPUR** system applies distributed artificial intelligence techniques in a decision support system for supervising a wastewater treatment plant. The processes of the plant are represented by agents, which collaborate in a layered architecture [74]. This supervisory integrated and distributed architecture proposes the integration of several interacting subsystems or agents, and the combination of problem solving capabilities, reasoning as well as learning tasks in a single structure. A real world application was delivered later in ATL-EDAR [75].

In the **EDS** (*Environmental Decision Support*) application an agent community is used for supporting the decision-making process related with environmental assessment, planning, and project evaluation. Specifically, the *EDS* system provides assistance to project developers in the selection of adequate locations of their projects (*e.g.* roads, industries, hospitals, *etc.*), guaranteeing the compliance with the applicable regulations and the existing development plans as well as satisfying the specified project requirements and the fulfilment of applicable regulations according to the location ([44], [45]).

The **SAEM** system (*A Society of Agents in Environmental Monitoring*) proposes the use of robotic agents that collaborate for monitoring and evaluating the pollution on a power plant chimney [76]. Specifically, a simulated application of small flying robotic agent societies (helicopter models) is assigned to go around a chimney in order to sample the pollutant cloud and to send values to a central processing unit which builds a global map. This map is then transformed into an image that holds information about cloud direction, pollutant concentration, *etc.*

allowing decision makers to evaluate and change the burning conditions of the power plant.

In the **ESAT-WMR** system (*Expert System and Agent Technology to Water Mains Rehabilitation*), the agent-based decision support tool reported intents to support a U.K. water company in its water mains rehabilitation decision making processes. A community of collaborative agents models the tasks and interactions of the water company and its associates, and, ultimately, assesses alternative strategies for the pipes network rehabilitation ([23], [24]).

The **IDS-DAP** system (*Intelligent decision support system for differentiated agricultural products*) is a DSS applied for the selection of agricultural product penetration strategy. It incorporates distributed multi-criteria analysis models. Concretely, the multi-criteria method UTASTAR is applied to the multi-criteria consumer preferences in order to determine the criteria explaining each of the consumer's choices into consumer agents participating in a particular market research ([49], [48]).

The **FIRMA** project (*Freshwater Integrated Resource Management with Agents*) applies agent-based modeling for the integration of natural, hydrologic, social and economic aspects of freshwater management. A variety of agent-based models has been developed for simulating consumers, suppliers, and government, and their interactions at different scale of aggregation. One of the *FIRMA* test cases has been applied on the Thames River to explore the effects of precipitation and temperature on water availability and household demand [12]. In this case, water consumer agents communicate with each other, sharing perspectives in the form of endorsement [54].

The **SHADOC** system (French acronym for *hydro-agricultural simulator describing organization and coordination modes*) uses agents for simulating the behavior of the stakeholders and the farmers involved in the irrigation of Senegal valley [9]. The model constitutes a virtual irrigated system which can already be used as a tool to test hypotheses of social organizations and institutions. This is still a theoretical simulator somewhat specific to the Senegal River Valley even though it has been designed to be able to deal with other contexts.

EDEN-IW (*Environmental Data Exchange Network for Inland Water*) is a system that aims to provide citizens, researchers and other users with existing inland water data, acting as a one-stopshop [25]. *EDEN-IW* exploits the technological infrastructure of *Infosleuth* system ([57], [66]), in which software agents execute data management activities and interpret user queries on a set of distributed and heterogeneous databases. Also, *InfoSleuth* agents collaborate for retrieving data and homogenizing queries, using a common ontology that describes the application field. *EDEN* pilot demonstration enables integrated access via web browser to environmental information resources provided by offices of the connected agencies. The demonstration focuses on information relating to remediation of hazardous waste contamination.

WaWAT (*WasteWater Agent Town*) employs several co-operative agents who make use of case-base reasoning, rule-based reasoning and reactive planning, to support supervision and control of wastewater treatment plants [18]. It uses the WaWO ontology (*Waste Water Ontology*) [19] which provides a set of concepts that can be queried, advertised and used to control agent cooperation.

The **BUSTER** system (*Bremen University Semantic Translator for Enhanced Retrieval*) utilizes ontologies for retrieving information sources and semantic translation into the desired format [56]. This approach can be applied when the information can be accessed by remote systems in order to supplement own data basis. The *BUSTER* approach provides a common interface to heterogeneous information sources in terms of an intelligent information broker. A user can submit a query request to the network of integrated data sources (*e.g.* as shown in a query example sampling information about the land use of a specific site).

Adour is a bargaining model to simulate negotiations between water users in a river basin [81]. A formal computable bargaining model of multilateral negotiations is applied to the Adour Basin case, in the South West of France, with seven agents (three "farmers", two "environmental lobbies", the water manager, the taxpayer) and seven negotiation variables (three individual irrigation quotas, the price of water, the sizes of three dams), in order to negotiate alternatives of water use. A sensibility analysis is conducted to quantify the impact of the negotiation structure (*e.g.* political weights of players, choice of players~~...~~) on simulations outcomes. The final aim is to provide a better understanding of the complex interrelations between the various components of the modeled system: preferences of stakeholders over negotiated variables, the role of exogenous (*i.e.* hydraulic and budgetary) constraints in the bargaining game, the consequences of the structure of negotiation (*e.g.* decision rule, players' weights, dimension of the issue space *etc.*) on the bargaining outcome *etc.*

DIAMOND (*DIstributed Architecture for MONitoring and Diagnosis*) adopts an agent-based architecture for distributed monitoring and diagnosis [2]. Industrial diagnostic systems aim at anticipating the occurrence of failures or, should failures have occurred, at detecting them and identifying their cause. *DIAMOND* will be demonstrated for monitoring of the water-steam cycle of a coal fire power plant, and for integrating a diagnostic system with an existing process control network.

The **MAGIC** system (*Multi-Agents-based Diagnostic Data Acquisition and Management in Complex Systems*) was created with the same purpose as *DIAMOND*. Even if it is not targeted only for environmental applications, its objective is to develop a flexible multi-agent architecture for the diagnosis of progressively created faults in complex systems, by adopting different diagnostic methods in parallel. *MAGIC* has been demonstrated in an automatic industrial control application [37].

A quite similar system that uses software agents for accessing environmental data is **NZDIS** (*New Zealand Distributed Information System*). *NZDIS* ([21],

[68]) has been designed for managing environmental meta-data in order to service queries to heterogeneous data sources. *NZDIS* software agents are used for submitting queries to environmental databases in a seamless way. Agents receive and reply to requests for services and information by means of a high level declarative agent communication language, whose message contents may be expressed in terms of formal ontologies that describe the vocabularies of various domains.

The **D-NEMO** experimental prototype, installed in the Athens Air Quality Monitoring Network, uses agents for the management of urban air pollution [36]. *D-NEMO* agents incorporate classification and regression decision trees, case based reasoning and artificial neural networks for forecasting collaboratively air pollution episodes.

The **RAID** system (*Rilevamento dati Ambientali con Interfaccia DECT*) deals with pollution monitoring and control in indoor environments. *RAID* exploits the general architecture of Kaleidoscope that uses "entities" for the dynamic integration of sensors [52]. The system is based on innovative sensors and wireless communication. It includes a knowledge-based supervisor aimed at identifying pollutant sources.

AqEcAA (*Aquatic Ecosystem Simulation with Adaptive Agents*) presents a conceptual framework simulating the aquatic food web and species interactions by using adaptive agents [70]. It provides a realistic framework for ecosystem simulation, evolving ecosystem structures and behaviors by emerging, submerging, interacting and evolving ecological entities.

the **CATCHSCAPE** system [13] deals with the irrigation of northern Thailand, using agents for representing all entities related with the hydrologic basin. Agents incorporate models for the determination of aquatic reservoirs with respect to future changes in drought conditions and changes in commodity prices, and farmer behavior.

The **SINUSE** application [26] employs agents to model the Kairouan water basin. *SINUSE* agent-based system investigates the consequences of human behavior in the availability of aquatic resources by simulating physical and socioeconomic interactions on a free access water table. *SINUSE* is considered as a first step in the use of MAS for groundwater studies, and it has proved the relevance of taking local and non-economic interaction into account in the case of the Kairouan water table.

The **STAU-Wien** application (*City-Suburb relations and development in the Vienna Region*) aims to study the urban growth of Vienna city and its suburbs. The objective of this work is to simulate prior and future landscape transition processes for the suburban region in the surroundings of Vienna, Austria. A spatial agent model is used for stimulating regional migration and allocation decisions of households and commercial enterprises [41].

The multi-agent model **GEMACE** (*Multi-agent model to simulate agricultural and hunting management of the Camargue and its effects*) simulates the interactions between hunters, farmers and duck population of a habitat. The system investigates the correlations between human activities and the environment and their impacts to the land use and the population of ducks [47].

The **FSEP** project (*Forecast Streamlining and Enhancement Project*) is being developed in the Australian Bureau of Meteorology, and uses agents for detecting and using data and services available in open, distributed environment. In *FSEP*'s pilot system [22], agents monitors in real time the current Terminal Area Forecasts (forecasts in areas around airports) and alerts forecasters to inconsistencies between these and observations obtained from the Automatic Weather Station data.

The **CANID** system employs autonomous agents for simulating the population dynamics of coyotes using the Swarm platform (Swarm Development Group 2001). The system models territoriality and dominance of canine populations and their effects on population dynamics and supports agent interaction with variable schedules and hierarchies [65]. The model was not tied to a specific geographic area and does not account for regional differences among populations (*e.g.* litter size, pack size or territory size). Additional model development may account for this variation with changes in resources among regions.

The **NED-2** application, developed by the University of Georgia and the USDA Forest Service, deals with the simulation of forest ecosystems management plans and the evaluation of alternatives. In *NED-2* agents use growth and yield models to simulate management plans, perform goal analyzes, and generate result reports [58]. *NED-2* uses blackboard architecture and a set of semi-autonomous agents to manage the different modeling tools used.

The **PICO** project [63] adopts agent-based requirement analysis for a decision support system in the field of integrated production in agriculture. This work focuses on design issues, using Tropos methodology [29] and continuing their developments using software agents.

In **$\mathbf{O_3}$RTAA** several software agents co-operate in a distributed agent society in order to monitor and validate measurements coming from several sensors, to assess air-quality, and to fire alarms when needed [6]. O_3RTAA relies on the agent paradigm for building intelligent software applications, while takes advantage of machine learning algorithms and data mining methodologies for extracting knowledge and customizing intelligence into agents. The system intervenes between the sensors and the experts and undertakes several tasks in order to assist humans in their evaluation. Specifically, system goals are assigned to agents that act as mediators and deliver validated information to the appropriate stakeholders.

In **AMEIM** (an *Agent-based Middleware for Environmental Information Management*) software agents undertake environmental data management tasks. The agents in *AMEIM* are capable to fuse and pre-process environmental data. *AMEIM* is a reusable platform, which realizes a generic architecture for developing agent-based systems, operating as a middleware application between environmental data pools and the final users of environmental information. Accordingly, the *AMEIM* system is fully customizable (depending on the requirements of each application) and, as mentioned before, follows an extendable architecture [7]. Reasoning capabilities can also be incorporated into *AMEIM* agents for supporting decision-support features.

DAWN (*Hybrid Agent-Based Model for Estimating Residential Water Demand*) is a simulator that integrates an agent-based social model for the consumer with conventional econometric models. It simulates the residential water demand-supply chain and thus, enables the evaluation of different scenarios for policy making. It was used to evaluate five different water-pricing policies for the period 2004-2010 in the metropolitan area of Thessaloniki [5]. Its main advantage is that it supports social interaction between consumers, through an influence diffusion mechanism, implemented via inter-agent communication (JADE and FIPA specifications).

FIRMABAR (*FIRMA* stands for *Freshwater Integrated Resource Management with Agents* and *BAR* for *Barcelona*) is an agent-based simulator, within the *FIRMA* project, aimed at simulating urban water management [42]. Such simulator provides the policy makers with an additional tool to evaluate alternative water policies in different scenarios. The simulator plays the life of a set of families (agents) on a grid that represents the territory. The global behavior of the simulation emerges as a result of the interaction of the individual agents through time (nothing in the model specifies the global-level behavior of the system). The step time in simulations is the month, and there are four central processes computed at each time step.

MANGA is a discrete event simulator (a sequential process of unrelated events) [39]. The objective of *MANGA* is to show, over a number of years (12-year period), the evolution of a group of farmer agents with a limited water resource. In *MANGA* the authors demonstrate that agent-based modeling could help negotiations by showing the consequences of water allocation rules with respect to different criteria (*e.g.* the climate of the year, the irrigated area and the level of irrigation).

MABEL (*Multi-Agent Behavioral Economic Landscape*) presents a bottom-up approach to allow the analysis of dynamic features and relations among geographic, environmental, human, and socioeconomic attributes of landowners, as well as comprehensive relational schematics of land-use change [40]. The authors adopt a distributed modeling architecture to separate the modeling of agent behaviors in Bayesian belief networks from task-specific simulation scenarios. *MABEL* has a client-server architecture, a key component that allows to simultaneously simulate land-use change over large regions in an efficient and scalable way. It separates the simulation locations from the agents' behavioral models, which simplifies the work required to parameterize these models for task specific use in the distributed modeling environment.

Control-MWS (*Agent-Based Control of a Municipal Water System*) implements a water pollution monitoring system of a simplified municipal water system (*i.e.* a single water reservoir, a single tank, a pump station with only one electrical pump, pipes and valves). It monitors the level and quality of water basically in the tanks and pumping stations, as strategic points to set up control strategies [28]. The authors use a distributed control architecture based on automation controllers with an extended firmware that supports intelligent agents. The intelligence of the system is distributed among multiple controllers by placing individual or multiple agents inside the controllers. After setting up some control strategies, simulations are done to predict the results in water quality under these control strategies.

GRENSMAAS is a project that started in the 1990s. Within the scope of this project the researchers [84] presented an agent-based model to evaluate different river management alternatives developed within the previous phases of the project. This agent-based model is coupled with an integrated river model that describes the impacts of river management, such as flood risk, nature development and costs (related to gravel extractions). Thus, the main use of the agent-based model is to investigate stakeholder environment interaction by simulating changing perspectives and behavior in response to environmental change. The agents are endowed with quantitative goal standards to evaluate their goals. The beliefs of the agents are related to their uncertainty perspectives for evaluating a river management strategy.

DSS MAS-GIS (*Decision Support System coupling Multi-Agent System and Geographical Information System*) is a framework developed to manage water in the Mediterranean islands. The MAS-GIS platform makes possible for users to better understand the current operation of the system and the evolution of the situation, while simulating different scenarios according to the selected water policies (*i.e.* best consumer water policies) and the climatic changes hypothesis [83].

PALM (*People And Landscape Model*) was used to simulate seven strategies of crop nutrient management used within a community of households (the model simulates resource flows in rural subsistence communities). *PALM* runs on a daily time step using daily weather data as driving variables. The model uses object-oriented concepts with multiple instances of various sub-models being possible. Consequently, as an example, different crop models (or even the same one) can be run simultaneously in different fields with different parameters (*e.g.* planting dates, *etc.*) for each instance. Its structure and the use of Object Oriented Programming (OOP) and agents allows a high degree of modularity, and hence flexibility ([51], [50]).

DANUBIA is a decision support system embedded in *GLOWA-Danube* project aimed at evaluating the sustainability of future water resources management alternatives, and to evaluate consequences of IPCC (Intergovernmental Panel on Climate Change) derived climate scenarios for the period from 2000 to 2100 [32]. *DANUBIA* is a coupled simulation system comprising 16 individual models [11]. To integrate the different simulation models *DANUBIA* makes use of object-oriented framework approaches. The agent-based approach, within the overall system, is used to model demography, water consumption and supply infrastructure, thus, to assess and simulate the socio-economic aspects of the water cycle (not the physical processes concerned with the water cycle). For that purpose a simulator -**DEEPACTOR**- was built providing a common conceptual and architectural basis for the modeling and implementation of the socio-economic simulation models in *GLOWA-Danube* [10].

WPMS (*Water Pollution Monitoring System*) is aimed at monitoring water quality for regulatory compliance. The water pollution monitoring system is comprised of several sites/stations in which the water quality is monitored, and when the measurements of certain parameters are exceeded, a warning is sent to the supervisor system. As the sites are geographically distributed, they are modeled in a natural way as intelligent agents that communicate with a supervisor agent who receive corresponding messages from the sites. A prototype has been designed for future implementation [60]. The system can also be used to facilitate response to contamination incidents.

Another application in coupling human and natural systems, in the area of *Land-Use Change Dynamics* (**LUCD**), is given by [53]. Land-use change dynamics were simulated for several scenarios, differentiated by the initial distribution of the different agents (*i.e.* landowner, homeowner and government types), and economic model assumptions. The goal of this work was to develop both a specific model for the study area and a general framework that captures essential features of land-use change dynamics. The used of multi-attribute key utility functions are the basis of agent rationality and decision-making.

The **SYPR** project (*Southern Yucatán Peninsular Region project*) aims at modeling and simulation of deforestation in this region. One of the main components is **HELIA** (*Human-Environment Integrated Land Assessment*). *HELIA* represents real-world households and their land-use strategies as virtual agents equipped with multi-criteria evaluation strategies and other methods (symbolic regression, and evolutionary programming). Another important component is **LUCIM** (*Land-Use Changes In the Midwest*). The latest uses a utility-maximization approach whereby a set of household land-use preference parameters are fitted to the land-change record derived from historical aerial photography [46].

MASQUE (*Multi-Agent System for supporting the Quest for Urban Excellence*) exploits the versatile potential of multi-agent technology for supporting the development of land use plans [73]. It gives a detailed description of the operation of agents who are part of the system's 'knowledge' component, and then, a prototype application is developed to demonstrate how multi-agent concepts can be used to generate alternative plans. It provides functionality to make inventories of a site, *i.e.* tools to input both spatial and a-spatial data about the study area and its surroundings in order to build up project databases.

The **Thieul** simulator was developed with the help of *CORMAS* programming environment [8]. The agent-based model has been designed to formalize the interactions between the biophysics dynamics of the natural resources (*e.g.* available water, land, *etc.*) and the socio-economic factors driving the land-use dynamics around the drilling of Thieul village in the sylvo-pastoral area of Ferlo (Senegal).

SIMULAIT WATER was used to analyze urban water trading and water saving incentives among households of differing demographic types. Each agent can mimic the behavior of individual elements (*e.g.* households) in a system, as well as their interactions (*e.g.* negotiations among households). In this case, agents model individual households and their purchasing and water consumption behaviors [64].

LUDAS (*Land-Use Dynamic Simulator*) is a multi-agent system to simulate spatio-temporal dynamics of coupled human-landscape system [38]. The system is aimed at explore alternative scenarios to improve livelihoods and mitigate negative impact of land-use changes, thereby supporting the negotiation process among various stakeholders in land-use planning. Human population and the landscape environment are all self-organized interactive agents that are called upon to perform tasks in parallel (*i.e.* synchronizing actions). The framework provides a platform where many techniques already developed in spatial modeling can be integrated. For instance, the authors nested the bounded-rational decision mechanism (*e.g.* the maximization of parameterized utility functions) with the reflex mechanism (set of reflex rules) to represent the decision making mechanisms of farming households about land use.

4. Analysis and Discussion

In §3 forty-two applications using, in a more or less extent, agent-based technology in the environmental management domain, have been briefly explained. In Tables 1–5 (see pp.22–26) and 6–7 (see pp.27–28) a summary is given, respectively, together with some important characteristics used to analyze the systems reviewed. These characteristics are quoted in §3 and make reference to *agent software design* and *software development* diffusion.

From the *software design* perspective, thirty of the applications use the notion of an agent to conceptualize the system under study. These are followed by eleven applications that adopt the notion of an agent not only to conceptualize the system but to specify the software as well. Still seven of the applications reviewed use a low level notion of agents, understanding the agents as simple agent-alike "*entities*". Finally, only three of the applications adopt a more sophisticated agent-oriented software process to design the system. This latest remark suppose that, whereas from 1996 to 2004 only one of the reviewed systems had used an agent-oriented software engineering technique throughout the whole design process (*i.e. PICO*), from 2005 to 2008 two more of the studied systems have used them (*i.e. AMEIM*, *WPMS*). As shown in Tables 6–7 some of the systems use, in the same application, different levels of software design. If such is the case, both notions considered have been noted.

Following the same perspective (*i.e.* software design), in Tables 1–5 the agent types (or names) used to model the systems are written. They can be classified in two general categories: one group containing agents that perform specific functions (*i.e.* knowledge base, case-based reasoning, supervisory, data provider, query, broker, ontology, wrapper agents) and a second group containing agents that represent physical objects (*i.e.* pump station, watercourse agent, *etc.*), persons (*i.e.* landowner, household, farmer, taxpayer, hunting manager, *etc.*) or institutions (*i.e.* environmental lobbies, families, government agents, *etc.*). That is, in the first category there are well-known knowledge base, data mining *etc.* tasks, whereas in the second category an *agentification* of several real entities takes place. These latest agents are commonly operated with an specific model describing their behavior.

From a *software development* perspective, the applications presented are generally developed with an object-oriented language. Sixteen of them implement the system with objects. Nevertheless, twelve of them use agent-based platforms. These platforms are either generic (*e.g.* Swarm, NetLogo, *etc.*) or specific builded platforms (*e.g.* SimulaitWater, DeepActor, *etc.*). Their implementation degree, if known, is generally either partially or fully developed prototype. None of them is reported to be fully implemented as a real-time application.

When analyzing the *validation* step, twenty seven of the applications are validated. As a first-step validation, the most extended method employed to validate agent-based applications is by means of expert validation of the model they use. As a second step, most of the applications permit to do some simulations and to compare the simulated results against historical and/or observed data (when available). Few of them use other, more sophisticated, techniques (*i.e.* sensitivity analysis, extreme tests or cases).

5. Conclusions

The *state of the art* in agent-based approaches applied to environmental issues shows the utility of agents as solvers of environmental problems. The applications and agents used are heterogeneous in nature: although most of them refer to natural resources management (*i.e.* from water sources, air or soil), other environmental issues are also faced using agents. Their coupled work permit to go beyond their individual capabilities or knowledge. All these applications have some of the general characteristics of Multi-Agent Systems (MAS) reported in [79]:

- Each agent has incomplete information or capabilities for solving the problem. Thus, the importance of MAS is concerned with the behavior of a collection of agents designed at solving a given problem together.
- There is no global system control.
- Data is decentralized, and
- Computation is asynchronous.

The design of the systems studied is mainly done using agent-based concepts whereas for their implementation the use of object-oriented technologies prevails. The systems are partially validated: in most of the cases the model used to describe the agents is validated through expert knowledge, whereas the overall system performance validation is a further step that requires more work and research to be done.

As concluded in [4], agent-based technology is not homogeneously adopted in environmental software developments. However, an increase in the use of agent platforms to develop the systems is observed. Even though the fuzzy classification of the systems into the three groups described in §3 (*i.e.* EDMS, EDSS, ESS), no interrelation between the type of agent-based environmental system and the technology used can be observed.

Design and implementation of MAS aimed at solving environmental problems require research in order to tackle with many challenges. Some of the most important and tricky ones were listed in [35], and are still important questions by researchers in the field of multi-agent system applications. Answers to these questions are naturally interrelated. Some answers are found within the systems reviewed in the *state of the art* here presented and some others are offered in this book for some specific environmental problems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
DAI-DEPUR [74][75]	Simulation and control of the physical, chemical, microbiological aspects of the activated sludge processes	Wastewater treatment plants	LISP, G2, GAR, LINNEO$^+$	Knowledge base agents, case-base reasoning agents, supervisory agents
EDS-DAI [44]	Project evaluation and assessment with respect to alternative locations that comply with legal regulations, development plans and satisfy custom requirements	Environmental project evaluation	Distributed Belief Revision, ARCHON	Decision Support Agents (or evaluation agents), Data Provider Agents (stored in GIS), User Interface Agent
SAEM [76]	Monitoring the pollutant cloud emitted by a power plant chimney	Atmospheric pollution	Robotic agents	Helicopter agents
ESAT-WMR [23] [24]	Modeling and analysis of elective strategies for urban water supply pipe network rehabilitation	Water supply networks	KIF, KQML, Object-oriented programming	Interface agent, Heuristics agent, Information agent, Data mining agent, Database agent, Constraint Agent, Predictor Agent, HotSpot Agent
IDS-DAP [49] [48]	market penetration of agricultural products investigation, using multicriteria analysis	Differentiated agricultural products marketing	UML, Visual Basic, TCP-IP, Java	Data analysis agent, Brand Choice agent, Market expert agent
FIRMA & Thames [54] [12]	Agent-based modeling for the integration of natural, hydrologic, social and economic aspects of freshwater management.	Water resource management	SDML	Policy agent, Citizens
SHADOC [9]	Farmer behavior and water allocation simulation	Water catchment management	UML, SmallTalk, Object-oriented programming, Petri Nets, CORMAS, Visual Works®	PumpStation, Reach, Watercourse, Farmer agents
EDEN-IW & InfoSleuth [57] [66] [25]	Data integration and homogeneous access provision services	Water resources data	JADE, FIPA-ACL, SQL, RDF, OKBC	DB resource agent, query decomposition agent, ontology agent, broker agent

TABLE 1. Summary of the reviewed systems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
WaWAT (WaWo) [18] [19]	A multi-agent cooperation infrastructure for supervision and deicision-making in wastewater treatment plants	Wastewater treatment plants	Ontolingua KSL Server	Dynamic *entitties* (monitoring, modeling, actuator, predictive agents, *etc.*)
BUSTER [56]	Data integration and filtering, querying services	Geographical information sources	OIL, FIPA-OS	Wrapper, mediator, mapper
Adour [81]	Stakeholder negotiation over water use	Water management	BDI	Farmers, environmental lobbies, water manager, taxpayer
MAGIC & DIAMOND [37] [2]	Fault detection in industrial process	Water treatment process and Water steam cycle a power plant	XML, CORBA, FIPA-ACL	Diagnostic agents, data acquisition agents, knowledge acquisition agent, wrapper agents, monitoring agent
NZDIS [21] [68]	Integrated querying services in an open, distributed environment of heterogeneous databases	Environmental data	FIPA-ACL, UML, OQL, RDF	Ontology agent, resource agent, query processing agents, broker agent
D-NEMO [36]	Air pollution incident forecasting	Atmospheric pollution	LALO, KQML	Station agents, model agents
RAID [52]	pollution monitoring and control in indoor environments	Indoor air quality	UML, Kaleidoscope	*entities*: manager, sensors, *etc.*
AdEcAA [70]	simulation of aquatic food webs and plankton species interactions	Food chain	Echo	Phytoplankton species, zooplankton species
CATCHSCAPE [13]	Simulation of the whole catchment features as well as farmer's individual decisions	Water catchment management	UML, SmallTalk, Object-oriented programming, CORMAS	Crop, Farmer, Canal, Weir, Canal Manager, River
SINUSE [26]	physical and socio-economic interactions modelling for simulating demand management negotiations on a free access water table	Integrated management of a water table	UML, SmallTalk, Object-oriented programming	Plot, Water table, Farmer
STAU-Wien [41]	Simulation or rural development patterns in the Vienna Region	Rural development	UML, ArcInfo, Cellular automata, Object-oriented programming	Enterprises, households

TABLE 2. (continued) Summary of the reviewed systems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
GEMACE [47]	Simulation of interactions between duch population, farming decisions and leasing of hunting rights	Environmental planning	UML, SmallTalk, Object-oriented programming, CORMAS	Hunting manager agents, farmer agents
FSEP [22]	Surveillance, forecasting and alert of weather conditions	Meteorology	JACK, RDF-S, DAML+OIL	Wrapper agents, interface agents
CANID [65]	Agent-based simulation of territoriality and cominance of canid populations	Biodiversity-population dynamics	Swarm	*coyote*, pack
NED-2 [58]	Forest ecosystem management simulation and goal-driven decision support	Forest management	C++, Prolog, HTML	Interface agent, Simulation agent, Goal analysis, planning agent
PICO [63]	Design system requirements, analysis of organizational complexity, dealing with all the dependencies between the domain stakeholders, and study of natural plant protection techniques.	Integrated production in agriculture	Tropos, WEKA	GIS agents, Disease Behavior Learner, wrapper agents
O_3RTAA [6]	A MAS for monitoring and assessing air-quality attributes, firing alarms to appropiate recipients when needed.	Urban Pollution Control (air)	JADE, FIPA-ACL, Protégé 2000 (exported in RDFS), WEKA, JESS, PMML	Diagnosis Agent, Database Agent, Distribution Agent, Alarm Agent
AMEIM [7]	A MAS able to capture and validate environmental data from several external sources.	Environmental data monitoring and management	GAIA, AORML, JADE, Protégé 2000, FIPA-ACL	Contribution Agents, Data Management Agents, Distribution Agents, Graphical User Interface Agent
DAWN [5]	Simulation of residential water demand and how water pricing policies affect demand	Water demand management	AORML, 2D grids, JADE	Simulator, meteo, consumer, supplier agents
FIRMABAR [42]	Integrated freshwater assessment in a geographic area by means of water supply/demand simulations (in different scenarios)	Urban water management	SDML, Swarm libraries (Java), OOP	Families, companies, municipalities, government agents

TABLE 3. (continued) Summary of the reviewed systems.

Acronym	Main tasks and objectives	Application Field	Related technologies	Agents (names or types)
MANGA [39]	Simulation of decision-making process and of the impact of water allocation on farmer's collective behavior	Rural development, water resources management	UML	Farmers, water suppliers, crops, climate, information supplier agents
MABEL [40]	Simulation of land-use changes over time and space	Land use	BDI architecture, Swarm, VisualStudio.NET C/ C++, BBN (Bayesan Belief Network)	Policy maker, land owners (farmer agent, ubrban residential agent, forestry agent, household agent, *etc.*)
Control-MWS [28]	Water pollution monitoring system (water quality, energy costs and demand) of a simplified municipal water system	Urban water data management	Simulink tool	Pumping station, tank agents
GRENSMAAS project [84]	Simulation of stakeholder support in under different policy stretegies (nature development, gravel extraction, flood reduction)	Water catchment management	BDI (approach)	Policy makers, citizens, farmers, nature organizations, gravel extractors agents
MAS-GIS DSS [83]	Decision support system framework for water management in the Mediterranean islands coupling a Multi-Agents System with a Geographic Information System	Water management	CORMAS, ARCGIS, ODBC	Drillings, tanks, water companies, consumers (hotels and homes), and a water police agents
PALM [50] [51]	Simulation of management strategies in a community of households in Nepal (linking decision-making to underlying biological processes in soil nutrient dynamics)	Rural development	UML, OOP	Household, landscape, livestock agents
DANUBIA (DEEP-ACTOR) [11] [10]	Simulation of scenarios and strategies for the future of water in the upper Danube Basin (an integrative decision support system)	Water resources management (water supply and groundwater) under conditions of global change	UML, object-oriented programming (OOP)	Farmer agents (maize, MeatBreed, *etc.*), WaterSuppliyCompany and Household agents

TABLE 4. (continued) Summary of the reviewed systems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
WPMS [60]	Water pollution monitoring for regulatory compliance (early stage of research; analysis phase)	Urban water management	FIPA-ACL, UML, GAIA	Monitor, supervisor and control agents
Thieul [8]	Simulation an agro-sylvopastoral context	Integrated natural resource management	UML, CORMAS	Farmers, herders and farmer-herders agents
LUCD [53]	Determining conditions of the interactions between human decisions and natural systems that lead to long-term sustainability of forest ecosystems	Land-use management, forest management	multi-attribute utility functions	Landowner, developer, home-owner, government agents
SYPR project (HELIA and LUCIM) [46]	Modeling land change and economic decision-making in the United States (LUCIM) and Mexico (HELIA)	Land-use management, forest management	evolutionary programming, multi-criteria evaluation, symbolic regression	Households agents (agriculturalists types)
MASQUE [73]	Multi-agent planning support system that supports decisions related to complex, uncertain and subjective urban planning problems.	Land use (urban)	BDI, UML, Borland JBuilderTM	Facilitation, interface, tool and domain (refer to land-use) agents
SIMULAIT WATER [64]	Simulation and analysis of various pricing and trading policies	Urban water management (supply and trading)	Scripting language	Household agents (low, medium and high)
LUDAS [38]	Spatio-temporal simulation of a coupled humanlandscape system.	Land-use and rural development	NetLogo 3.0	Household, landscape, agricultural agents

TABLE 5. (continued) Summary of the reviewed systems.

Acronym	SW Design	SW Dev.	Implementation Degree	Validation
DAI-DEPUR	2,3	D	Partial. The rule-based component and the case-based component were implemented, but not interconnected. It was continued in the WaWAT (WaWo) system. Also, a real-world application was delivered in the ATL-EDAR system [75].	Is incrementally being done at several points during its development. Whole system validation at three levels (1) simulation of the plant in real time, (2) building-up and testing on a pilot scale plant, and (3) validation on a real plant
EDS-DAI	2	C	The system prototype is under development	Two stages of evaluation : (1) Submission to the relevant group of public (and private) agencies, (2) Incorporation of consulted agencies' opinions
SAEM	2	D	Unkwnon	The use of simulation gives the chance of testing this kind of behaviours without building the real agents
ESAT-WMR	3	D	Partial	No
IDS-DAP	2	A	Unknown	No
FIRMA & Thames	1, 2	A	Full	Validation of model struct. and simulation results with stakeholders (focus groups) (comp. validation)
SHADOC	2	A	Full	Expert validation
EDEN-IW & InfoSleuth	2, 3	C	Partial (EDEN-IW DEMO available)	No
WaWAT (WaWo)	2,3	D	A prototype	Through some case study
BUSTER	2	B	A first prototype	No
Adour	3		Future Implementation in a case study (Adour Basin)	No
MAGIC & DIAMOND	2, 3	A, B	Core toolkit developed	Evaluation examples. Comparison values with simulated offline and online ones
NZDIS	2	B	Full	Unknown
D-NEMO	3	C	Full	Experimental multiagent prototype under simulated real time conditions
RAID	1	A	Unknown	Unknown
AdEcAA	2	A	An example of individual-based adaptative agents simulation system is implemented on the Echo framework	Through a multivariate time-series database for nine lakes different in climate, eutrophication and morphology

TABLE 6. Deep analysis of the reviewed systems.

Acronym	**SW Design**	**SW Dev.**	**Implementation Degree**	**Validation**
CATCH-SCAPE	2	A	Some prototypes	Comparison of the average simulated yields with those provided by local Thai Agencies
SINUSE	2	A	Full	Two step validation: 1) Extreme tests, 2) Partial sensitivity analysis
STAU-Wien	2	A	Full	No
GEMACE	2	A	Some prototypes	Expert validation
FSEP	2	C	A prototype	Through comparison between observed and forecasted data
CANID	2	C	Unknown	Comp. with other models; sensitivity analysis and calibration methods
NED-2	2	A, D	A prototype	Planned
PICO	4		No	No
O_3RTAA	2, 3	C	Full	In a single meteorological station. Extended validation planned.
AMEIM	4	C	Full (AMEIM ver.1.0)	Unknown
DAWN	2	C	Full	Metropolitan Area of Thessaloniki (under 5 scenarios). Expert validation
FIRMA-BAR	2	C	Full	Barcelona and Valladolid (under several scenarios). Expert validation
MANGA	2	A	Full	Qualitative
MABEL	3	C	Full	Against historical data
Control-MWS	1	A	Full	In a municipal wastewater system
GRENS-MAAS	3	A	Partia	Comparison with historical data
MAS-GIS DSS	1	C	A prototype	Expert validation
PALM	2	A	Partial	Two step validation: 1) Comp. with historical data, 2) Expert validation
DANUBIA (DEEP-ACTOR)	2	D	Full (not yet avail. for the interested end users, *i.e.* governm. institutions)	Two step validation: 1) Comparison with observed values; 2) Expert validation
WPMS	4		No	No
Thieul	2	C	Full	Expert validation
LUCD	1, 2		Full (optimization of utility functions)	Comparison with real data
SYPR (HELIA and LUCIM)	1, 2		Full (optim. of utility funct. and use of multi-criteria, symb. regression and evol. progr.)	Comparison of experimental data with expert knowledge
MASQUE	3	A	A prototype	Planned
SIMULAIT WATER	1, 2	D	A prototype	No
LUDAS	2	C	Full	Model validation in progress

Table 7. (continued) Deep analysis of the systems reviewed.

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