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A logic-based environmental decision support system for the management of horizontal subsurface constructed wetlands

Dario Garcia-Gasulla[a,*], Manel Poch[c], Juan Carlos Nieves[b], Ulises Cortés[a], Claudia Turon[d]

[a] Knowledge Engineering and Machine Learning Group (KEMLg), Universitat Politècnica de Catalunya (UPC), Spain
[b] Department of Computing Science, Umeå University, SE-901 87, Umeå, Sweden
[c] Institut Català de Recerca de l'Aigua (ICRA), H2O Building, Scientific and Technological Park, University of Girona, Emili Grahit 101, E17003, Girona, Spain
[d] Sanejament Intel· ligent S.L. (SISLtech), Av. Sant Julià 241, 08403, Granollers, Barcelona, Spain

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ABSTRACT

The use of Horizontal Subsurface Constructed Wetlands (HSCWs) for treating wastewaters in small communities has increased in the last years due to HSCW's ecological singularities. Unfortunately, the same singularities that differentiate HSCWs complicate any attempt to develop models and produce generic decision-support systems for them. Classical mathematical and statistical approaches used in other Wastewater Treatment Plants do not properly fit the particularities of HSCW and provide little insight in the domain of HSCW. We introduce a novel approach based on logic-based declarative specifications, *i.e.* non-monotonic causal logic, to capture explicit and implicit knowledge about HSCWs. By expressing all the relevant aspects of a HSCW in a declarative way, we produce a logic-based model which captures features that other approaches fail to formalize. At the end, we produce a complete decision-support system based on that model and test it against a set of realistic scenarios validated by experts. We discuss in which aspects this approach performs better than the most commonly proposed solutions in the bibliography and why it does so.

1. Introduction

Constructed wetlands are one of the most recommended technologies to treat wastewater in small communities (Turon et al., 2009). Both the use and the scientific interest on constructed wetlands to wastewater treatment have grown significantly (Greenway, 2005; Kivasi, 2001; Puigagut et al., 2007; Zhang et al., 2010; Vera et al., 2011) in the last years. This fact confirms the growing interest in industry and academia on this technology, Horizontal Subsurface Constructed Wetland (HSCW) being one of the most reliable sanitation technologies around the world (Rousseau et al., 2004; Masi and Martiruzzi, 2007; Barbatunde et al., 2008; Zhang et al., 2009; Vymazal, 2011).

Within an HSCW, chemical, biological, physical and even meteorological factors play a key role in its operation. The combination of all these elements brings along a huge complexity when trying to model the behavior of its environmental processes. The complexity lies not only on the multi-disciplinary knowledge required to understand its behavior, but also in the need to comprehend the huge set of interrelations there can be between the factors defining our domain. Every measured factor has a large set of causes and effects outside its own scope, *e.g.* mechanical factors can be affected by meteorological changes, biological factors can be caused by physical settings, *etc.* But those causes and effects must be understood in order to achieve an acceptable level of efficacy in the management of the HSCW. Moreover, every action available to the plant manager has also a set of changing side-effects depending on the current conditions of the HSCW. For a plant manager, to understand each and every cause, effect and condition of the domain, and to keep them on mind during the decision-making process, can be a difficult task. If we also consider the significant degree of uncertainty affecting HSCWs, given that most elements cannot be predicted or measured with absolute accuracy, that task becomes even harder.

In this context the huge number of publications is the proof of recent advances done in the design, construction, operation and maintenance of HSCW (Lee and Scholz, 2006; Rousseau et al., 2004; Turon et al., 2007; Zhang et al., 2009). But, despite this progress, there are still some contradictions in how to properly build and manage a HSCW, since there is disperse and uncertain knowledge related to it (Turon et al., 2007; Belia et al., 2009). To confront

* Corresponding author at: C/Jordi Girona, 1-3, UPC Campus Nord, 08034, Offices K2M-201/K2M-202, Barcelona, Spain. Tel.: +34 934134011; fax: +34 934017014.
E-mail addresses: dariog@lsi.upc.edu (D. Garcia-Gasulla), mpoch@icra.cat (M. Poch), jcnieves@cs.umu.se (J.C. Nieves), ia@lsi.upc.edu (U. Cortés), cturon@sisltech.net (C. Turon).

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those shortcomings lots of studies and projects have been made and several models and Intelligent Decision Support Systems (IDSS) have being designed and implemented. The great majority of these new developments recommend the most suitable configuration and design according to the characteristics of the influent and the required effluent limits (Anderssen et al., 1996; Pastor et al., 2003; Rousseau et al., 2004; Goossen et al., 2007; Turon et al., 2008; Langergraber et al., 2009; Giraldi et al., 2010). Some of these approaches are developments to forecast the removal capacity of pollutants (Lee and Scholz, 2006; Akratos et al., 2009; Langergraber et al., 2009; Giraldi et al., 2010). In Turon et al. (2007), an environmental IDSS approach was conceived to support the management, defining a protocol to prevent, detect and solve problems according to the configuration, design and placement of the constructed wetland.

It is at this point, when there is a lot of available knowledge regarding how the HSCW behaves that an IDSS can be useful. Such a tool should focus on the domain particularities which complicate the decision-making process, and provide help to solve the existing problems. A multi-disciplinary and complete analysis of those problems must be done to obtain a complete representation of the task to be solved. After that it seems necessary to find formalisms which allows to represent the information of the domain and its problems in a coherent and computable way. Hence, an adapted implementation of the domain and its problems is necessary to codify them using the selected formalism.

With such implementation available, the variables/observations which emerge from an operation process in a HSCW can be interpreted and used for decision making tasks in various ways:

- To explain the current operational problems of a HSCW by considering previous actions, *e.g.* the current color of most plants is yellow, there is also a plague of weeds together with a clogging of the distribution systems. What previously performed actions may have caused the current state?
- To predict potential operational problems of a HSCW, *e.g.* it is currently raining heavily, and the distribution of the plants has been observed to be non-homogeneous. What problems may there be now or may appear in the future?
- To suggest solutions to current operational problems of a HSCW, *e.g.* right now there are rodents within the HSCW and the dikes are observed to be in an abnormal state. What must be done to get rid of the rodents, fix the dikes while guaranteeing that the plants remain in an optimal state?

To manage an integrated form the variables/observations of an operation process in HSCW, and to give answer to the questions which emerge from these variables is a challenge for any current IDSS. Hence, the exploration of emerging approaches for knowledge representation and decision-making inferences seems necessary. The use of knowledge-based systems has been shown to be a suitable approach to support decision-making processes in environmental systems (Aulinas et al., 2011; Nieves et al., 2012). In fact, according to Mikulecký et al. (2007) knowledge-based approaches can help significantly to improve the efficiency and effectiveness of decision-makers' responses to a number of important or even dangerous situations that occur in wastewater systems. Thus, it is important to find ways to model and integrate the cause–effect relationships of management actions and to effectively represent that knowledge in order to support decision making in environmental systems like HSCW.

In knowledge representation techniques, one can find several candidate approaches for managing the operational variables of a HSCW in an integrated form (Baral, 2003; McCain and Turner, 1997; Rusell and Norvig, 2003). Some basic requirements for these candidate approaches are at least to support:

- Non-deterministic actions, *e.g.* a plant may react positively or not to a change of substrate.
- Continuous change, *e.g.* quantitatively, the water level is ever changing.
- Change in the absence of actions, *e.g.* at any time, with no apparent cause, it can start raining.

These requirements are naturally motivated by the operational singularities of any HSCW. Additionally, the maintenance of the knowledge base of an IDSS is expected to be transparent so that anyone can update it. In this setting, action specification languages seem to be good candidate specification languages for supporting decision making in HSCW (Baral, 2003; McCain and Turner, 1997; Gebser et al., 2010; Eiter et al., 2003). Among the different action specifications which can be found in the literature, those which are based on non-monotonic formalisms have shown to be expressive enough for capturing sophisticated domains, including: space shuttle (Nogueira et al., 2001), Biological Networks (Dworschak et al., 2008), Social Norms (Panagiotidi et al., 2009; Garcia-Gasulla et al., 2010), and dynamic domains (Akman et al., 2004). The formalizations of these languages are based on different formal methods. In particular, the nonmonotonic causal theory approach introduced in McCain and Turner (1997) represents an integral frame based on the so-called causal logic. The action specification language of causal logic is called *C+*. Furthermore, there is an implementation in Prolog of that language called the Causal Calculator (*CCalc*) which answers queries about action domains described in the C+frame. Currently, C+has been proven to be useful and effective in capturing complex dynamic domains and reasoning with them (Akman et al., 2004; Lifschitz et al., 2000).

CCalc (Giunchiglia et al., 2004) has also been used for capturing environmental domains, providing positive results. In Garcia-Gasulla et al. (2010), it was proven that CCalc is capable of representing most of the features found in real life which impair the performance of other solutions. However, action specification languages based on non-monotonic logics, such as CCalc, have not been used so far to produce a full and detailed environmental model. Designing and using such model brings forward a set of difficulties which we will try to solve in this article. To properly pursue that line of work, a complete IDSS must be produced in order to prove the capability of those action languages of becoming an integrated part of a fully interactive system for mainstream use.

In this article, we introduce a knowledge-based system called *EPSILoN* (Environmental Problem Solving Interface LOgic Nonmonotonic) which is capable of providing decision support for HSCW while capturing the complexities of them. EPSILoN is based on nonmonotonic causal theories; hence, it is able to model, not only the elements composing the HSCW, but also time and its relation with the HSCW processes. As a result, EPSILoN will be capable of understanding the current state of HSCW, identifying potential problems taking place, considering the temporal behavior of the basic elements of HSCW and proposing sets of actions with the goal of solving problems (currently taking place or in the future) in the monitored HSCW.

The paper is organized as follows. In Section 2 the methodology followed is introduced, including the used formalism and a proposal of domain extraction. In this same section the queries which will be used to obtain information from the system are also presented. In Section 2.4 the EPSILoN system is introduced, which integrates all the previous methodologies. In Section 3, three different tests performed with the system are described. In Section