Universitat de Girona

EDSS-MAINTENANCE PROTOTYPE: AN ENVIRONMENTAL DECISION SUPPORT SYSTEM TO ASSESS THE DEFINITION OF OPERATION AND MAINTENANCE PROTOCOLS FOR HORIZONTAL SUBSURFACE CONSTRUCTED WETLAND

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EDSS-maintenance prototype

An environmental decision support system
to assess the definition of operation and maintenance protocols
for horizontal subsurface constructed wetlands

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PhD Thesis

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Certifiquen

Que l'Enginyera Agrònoma Clàudia Turon Planella ha realitzat, sota la seva direcció, el treball que amb el títol "**EDSS-maintenance prototype: An environmental decision support system to assess the definition of operation and maintenance protocols for horizontal subsurface constructed wetlands",** es presenta en aquesta memòria la qual constitueix la seva Tesi per optar al Grau de Doctora en Medi Ambient per la Universitat de Girona.

I perquè en prengueu coneixement i tingui els efectes que corresponguin, presentem davant la Facultat de Ciències de la Universitat de Girona l'esmentada Tesi, signant aquesta certificació a

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Manel Poch Espallargas | Joaquim Comas Matas | Ulises Cortés Garcia

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T'hi espero!!!

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Resum

El tractament d'aigües residuals ha esdevingut un tema ambiental fonamental per al manteniment de la qualitat dels recursos hídrics. En aquesta línia, la Directiva Europea 91/271 fixa les pautes per a les Estacions Depuradores d'Aigües Residuals (EDAR) en termes de tipus de tecnologia i nivell de tractament requerit.

Sigui quina sigui la tecnologia i el nivell de tractament requerits, les EDAR es poden considerar sistemes complexos perquè es tracta de dominis mal estructurats que es basen en processos de depuració dinàmics i poc definits. Aquests factors (domini i processos) dificulten el manteniment de l'eficàcia dels processos de depuració. El manteniment de la qualitat de l'efluent de les EDAR és un aspecte molt important, no tan sols per a les regulacions ambientals i socials cada vegada més restrictives, sinó també per motius econòmics.

Les característiques especials de les EDAR fan que els models numèrics convencionals no siguin suficients per a un bon maneig quan (1) l'estat dels processos de les EDAR estan lluny del seu estat operacional normal i (2) el raonament amb informació qualitativa és essencial per tractar els problemes. En aquest sentit, els Sistemes d'Ajuda a la presa de Decisions en dominis Ambientals (SADA) han generat moltes expectatives com a eines per afrontar la complexitat associada al maneig de les EDAR. Un SADA es pot definir com un *software* interactiu, flexible i adaptable, que combina models/algoritmes numèrics amb tècniques basades en el coneixement, informació geogràfica i ontologies ambientals, i dóna suport als responsables ambientals en les eleccions entre alternatives. Els SADA permeten (1) manejar grans volums de dades; (2) incorporar coneixement expert; (3) afrontar la incertesa de les dades i del coneixement; (4) integrar les dades i el coneixement, a través de diversos models, en un *software*; (5) avaluar alternatives múltiples; (6) diagnosticar una situació anormal i proposar una teràpia per a solucionar els problemes i (7) proporcionar solucions *offline* o *online*.

Aquesta tesi s'ha desenvolupat en el marc d'un projecte que té per objectiu la construcció d'un SADA per donar suport a la definició de protocols d'operació i manteniment per a EDAR petites. Aquestes instal·lacions tenen un maneig més complex que les grans EDAR perquè l'escassa disponibilitat de recursos econòmics, humans i tècnics limita el correcte funcionament d'aquestes instal·lacions. Una tecnologia comú a les EDAR petites és la de Sistemes d'Aiguamolls Construïts de Flux Subsuperficial Horitzontal (SAC de FSH). Per aquest motiu, l'objectiu principal d'aquesta tesi és desenvolupar un SADA per donar suport a la definició de protocols d'operació i manteniment per a SAC de FSH (SADA-manteniment prototip). Un altre objectiu d'aquesta tesi és proporcionar algunes pautes per a desenvolupar un SADA que englobi les tecnologies de tractament més comuns en EDAR petites (SADA-manteniment) (2. Objectius).

El primer pas per assolir l'objectiu de la tesi va ser la selecció d'una metodologia per a desenvolupar el prototip del SADA-manteniment. Vam escollir la metodologia de cinc etapes proposada per Poch *et al.* (2004) perquè (1) ha estat aplicada amb èxit en la construcció de set SADA en el marc de la gestió de l'aigua i (2) proporciona certa flexibilitat per adquirir i integrar les dades i el coneixement requerits per a solucionar els problemes ambientals de l'aigua, i per representar aquesta informació a través de diversos models (3. Metodologia per a desenvolupar un SADA).

El desenvolupament del SADA-manteniment va començar amb l'anàlisi del problema ambiental (4.1. Anàlisi del problema ambiental). Una àmplia recerca bibliogràfica va permetre caracteritzar la complexitat associada a les EDAR petites i a la tecnologia dels SAC de FSH. A partir d'aquesta informació es van identificar els requeriments per a desenvolupar el prototip del SADA-manteniment. Aquesta informació es va obtenir de diverses fonts: (1) literatura, (2) una enquesta distribuïda a 13 EDAR petites que es basen en la tecnologia de SAC de FSH i (3) visites. Totes les dades i coneixement obtinguts van ser analitzats utilitzant la categorització, i després es van organitzar en termes de: problemes, modes, efectes, causes, controls i accions. D'aquest estudi es van identificar i caracteritzar 18 problemes (4.2. Adquisició de dades i coneixement).

El pas següent en el desenvolupament del prototip del SADA-manteniment va ser la selecció d'una metodologia per a representar les dades i coneixement adquirits. Després d'una anàlisi d'aquesta informació i dels mètodes disponibles per a la representació vam escollir el Sistema Basat en Regles (SBR). En aquest pas també es van seleccionar Java i Drools com a *software* per a construir el prototip del SADA-manteniment (4.3. Selecció del model).

En la fase següent va tenir lloc la representació de les dades i el coneixement adquirits segons la metodologia de SBR. En primer lloc, la informació dels SAC de FSH es va organitzar en 37 arbres de decisió i una matriu. A continuació aquesta informació es va traduir en regles del tipus IF-THEN, travessant cada branca dels arbres de decisió de l'arrel a la fulla o creuant les columnes i les files a la matriu (4.4. Implementació i integració dels models).

Un pas important en el desenvolupament del prototip del SADA-manteniment va ser el procés d'avaluació que té per objectiu verificar si hem construït el sistema correctament i validar si hem construït el sistema correcte. Per a realitzar aquesta avaluació vam proposar una metodologia basada en quatre passos: (1) verificació, (2) validació de laboratori amb dades històriques, (3) validació de laboratori amb experts i (4) validació de camp. Aquesta metodologia inclou dues funcions matemàtiques per quantificar l'eficàcia del SADA (4.5. Procés d'avaluació).

Al llarg del desenvolupament del prototip del SADA-manteniment es van fer una sèrie de recomanacions per a desenvolupar el SADA-manteniment complet. Aquestes propostes es basen en les modificacions fetes en la metodologia de cinc etapes i en l'experiència adquirida durant el desenvolupament del prototip del SADA-manteniment. El primer objectiu d'aquestes recomanacions és millorar l'adquisició de les dades i del coneixement (quantitat i qualitat). Llavors aquestes recomanacions se centren en l'anàlisi i representació d'aquesta informació, i conclouen amb uns consells per al procés d'avaluació del SADA-manteniment.

En la tesi també es presenta el funcionament del prototip del SADA-manteniment desenvolupat i un exemple de protocol d'operació i manteniment per a un SAC de FSH particular, per il·lustrar les capacitats del prototip del SADA-manteniment (5. Funcionament del prototip del SADA-manteniment).

Finalment, en el capítol 6 (6. Conclusions) s'enumeren les conclusions principals derivades d'aquesta tesi i es presenten alguns reptes a afrontar en el futur.

Resumen

El tratamiento de aguas residuales se ha convertido en un tema ambiental importante porque desempeña un papel fundamental para la calidad de los recursos hídricos. En esta línea, la Directiva Europea 91/271 fijó las pautas para las Estaciones de Depuración de Aguas Residuales (EDAR) en términos de tipo de tecnología y del nivel tratamiento.

Sea cual sea la tecnología y el nivel de tratamiento requeridos, las EDAR se pueden considerar como sistemas complejos porque son dominios mal estructurados que se basan en procesos de depuración dinámicos y mal definidos. Estos hechos (dominio y procesos) dificultan el mantenimiento de la eficacia de depuración. El mantenimiento de la calidad del efluente de las EDAR es un aspecto muy importante no sólo debido a regulaciones ambientales y sociales cada vez más restrictivas sino también por razones económicas.

Las características especiales de las EDAR hacen que el uso de modelos numéricos convencionales no sea suficiente para un buen manejo cuando (1) el estado de los procesos de las EDAR están lejos de su estado operacional normal y (2) el razonamiento con la información cualitativa es esencial para ocuparse de estos problemas. En este sentido, los Sistemas de Ayuda a la toma de Decisiones en dominios Ambientales (SADA) han generado altas expectativas como herramientas para abordar la complejidad asociada al manejo de EDAR. Un SADA se puede definir como un *software* interactivo, flexible y adaptable, que combina modelos/algoritmos numéricos con técnicas basadas en el conocimiento, información geográfica y ontologías ambientales, y apoya a los responsables ambientales en las elecciones entre las alternativas. Los SADA permiten (1) manejar grandes volúmenes de datos; (2) incorporar conocimiento experto; (3) abordar la incertidumbre de los datos y del conocimiento; (4) integrar los datos y el conocimiento, a través de diversos modelos, en un *software*; (5) evaluar alternativas múltiples; (6) diagnosticar una situación anormal y proponer una terapia para solucionar esta problemática y (7) proporcionar soluciones *offline* o *online*.

Esta tesis se ha desarrollado dentro de un proyecto que tiene por objetivo la construcción de un SADA para apoyar la definición de protocolos de operación y mantenimiento para EDAR pequeñas. Estas instalaciones son más complejas de manejar que las EDAR grandes porque la escasa disponibilidad de recursos económicos, humanos y técnicos limita el correcto funcionamiento de estas depuradoras. Una tecnología común en EDAR pequeñas es el Humedal Construido de flujo Subsuperficial Horizontal (HCSH). Por este motivo, el objetivo principal de esta tesis es desarrollar un SADA para apoyar la definición de protocolos de operación y mantenimiento para HCSH (SADA-mantenimiento prototipo). Otro objetivo de esta tesis es proporcionar algunas pautas para desarrollar un SADA que abarque las tecnologías de depuración más comunes en EDAR pequeñas (SADA-mantenimiento) (2. Objetivos).

El primer paso para alcanzar el propósito de la tesis fue la selección de una metodología para desarrollar el prototipo del SADA-mantenimiento. Elegimos la metodología de cinco pasos propuesta por Poch *et al.* (2004) porque (1) ha sido aplicada con éxito en la construcción de siete SADA en el marco de la gestión del agua y (2) proporciona cierta flexibilidad para adquirir e integrar los datos y el conocimiento requeridos para solucionar los problemas ambientales del agua, y para representar esta información a través de diversos modelos (3. Metodología para desarrollar un SADA).

El desarrollo del prototipo del SADA-mantenimiento empezó con el análisis del problema ambiental (4.1. Análisis del problema ambiental). Una amplia búsqueda literaria permitió caracterizar la complejidad asociada a las EDAR pequeñas y a la tecnología de HCSH. A partir de esta información se identificaron los requerimientos para desarrollar el prototipo del SADA-mantenimiento. Esta información fue adquirida a partir de diversas fuentes: (1) literatura, (2) un cuestionario distribuido a 13 EDAR pequeñas que se basan en tecnología de HCSH y (3) visitas. Todos estos datos y conocimiento fueron analizados usando la categorización y después fueron organizados en términos de: problemas, modos, efectos, causas, controles y acciones. A partir de este estudio identificamos y caracterizamos 18 problemas (4.2. Adquisición de datos y conocimiento).

El paso siguiente en el desarrollo del prototipo del SADA-mantenimiento fue la selección de una metodología para representar los datos y el conocimiento adquiridos. Después de un análisis de esta información y de los métodos disponibles para la representación elegimos el Sistema Basado en Reglas (SBR). En este paso también se seleccionaron Java y Drools como *software* para construir el prototipo del SADA-mantenimiento (4.3. Selección modelo).

La fase siguiente fue la representación de los datos y el conocimiento adquiridos según la metodología de SBR. En primer lugar, la información de HCSH fue organizada en 37 árboles de decisión y una matriz. Entonces esta información fue convertida en reglas de IF-THEN, atravesando cada rama de los árboles de decisión de la raíz a la hoja o cruzando las columnas y las filas en la matriz (4.4. Implementación e integración de los modelos).

Un paso importante en el desarrollo del prototipo del SADA-mantenimiento fue el proceso de la evaluación que tiene por objetivo verificar si hemos construido el sistema correctamente y validar si hemos construido el sistema correcto. Para realizar esta evaluación propusimos una metodología basada en cuatro pasos: (1) verificación, (2) validación de laboratorio con datos históricos, (3) validación de laboratorio con expertos y (4) validación de campo. Esta metodología incluye dos funciones matemáticas para cuantificar la eficacia del SADA (4.5. Proceso de evaluación).

A lo largo del desarrollo del prototipo del SADA-mantenimiento se hicieron varias recomendaciones para desarrollar el SADA-mantenimiento completo. Estas sugerencias se basan en las modificaciones de la metodología de cinco pasos y en la experiencia adquirida durante el desarrollo del prototipo del SADA-mantenimiento. El primer objetivo de estas recomendaciones es mejorar la adquisición de los datos y del conocimiento (cantidad y calidad). Luego, estas recomendaciones se centran en el análisis y en la representación de esta información, y concluyen con unos consejos para el proceso de evaluación del SADA-mantenimiento.

En la tesis también se presenta el funcionamiento del prototipo del SADA-mantenimiento desarrollado y un ejemplo de protocolo de operación y del mantenimiento para un HCSH particular, para ilustrar las capacidades del prototipo del SADA-mantenimiento (5. Funcionamiento del prototipo del SADA-mantenimiento).

Finalmente, en el capítulo 6 (6. Conclusiones) se enumeran las conclusiones principales derivadas de esta tesis y se presentan algunos retos a solucionar en el futuro.

Abstract

Wastewater treatment has become an important environmental issue because it plays a fundamental role in keeping natural water resources at as high quality as possible. In this line, the European Directive 91/271 set up the guidelines to Wastewater Treatment Plants (WWTPs) in terms of type of technology and treatment level.

Whatever the technology and the treatment level required, WWTPs can be considered complex systems because they are ill structured domains which are based on non-static and ill-defined purification processes. These facts (domain and processes) make it difficult to reach reliable good treatment efficiency. The maintenance of the standpoint of the effluent is a very important issue not only because of more and more restrictive environmental and social regulations but also for economical reasons.

The special characteristics of WWTPs require more than a straightforward application of conventional numerical models to obtain optimal management when (1) the process state of the WWTP is far from its normal operational state and (2) reasoning with qualitative information is essential to dealing with problems. In this respect, Environmental Decision Support Systems (EDSSs) have generated high expectations as tools to tackle the complexity associated with WWTP management. An EDSS can be defined as interactive, flexible and adaptable software, which links numerical models/algorithms with knowledge-based techniques, geographical information and environmental ontologies, and are developed to support environmental decision-makers in choosing between alternatives. EDSSs allow (1) to manage huge volumes of data; (2) to handle expert knowledge; (3) to tackle the uncertainty of data and knowledge; (4) to integrate both data and knowledge, through different models, into a software; (5) to accurately evaluate multiple alternatives; (6) to diagnose an abnormal situation and propose a therapy to solve this problematic event and (7) to provide objective offline/online proposals.

The present thesis has been developed within a project which aims to build an EDSS to support the definition of operation and maintenance protocols for small WWTPs. These facilities are more complex to manage than large WWTPs because the scarce availability of economic, human and technical resources limits the correct functioning of these facilities. A common small WWTP technology is the Horizontal Subsurface Constructed Wetland (HSCW). Hence, the main objective of this thesis is to develop an EDSS to support the definition of operation and maintenance protocols for HSCWs (EDSS-maintenance prototype). Moreover, this thesis also aims to provide some guidelines to develop an EDSS which comprise all common small WWTP technologies (EDSS-maintenance) (2. Objectives).

The first step to achieve our purpose was the selection of a methodology to develop the EDSS-maintenance prototype. In this respect, we choose the five-step methodology proposed by Poch *et al.* (2004) because (1) it was successfully applied in the construction of seven EDSSs in the water management framework and (2) it provides a certain flexibility to acquire and integrate data and knowledge required to solve water environmental problems, and to represent this information through different models (3. Methodology for developing an EDSS).

The development of the EDSS-maintenance prototype started with the analysis of the environmental problem (4.1. Environmental problem analysis). A wide literature research allowed characterizing the

complexity associated to small WWTPs and the HSCW technology. Moreover, this domain analysis permitted to define the requirements to develop the EDSS-maintenance prototype. This information was acquired from different sources: (1) literature research, (2) a questionnaire distributed to 13 small WWTPs based on HSCW technology and (3) onsite visits. All these data and knowledge was analysed using categorization and then was organized in terms of: problem, modes, effects, causes, measures and actions. From this study we identified and characterized 18 problems (4.2. Data collection and knowledge acquisition).

Next step in the development of EDSS-maintenance prototype was the selection of a methodology to represent the acquired data and knowledge. After an analysis of these information and the available representation methods we choose Rule-Based System (RBS). In this step Java and Drools were also selected as the adequate software tools to build the EDSS-maintenance prototype (4.3. Model selection).

The following phase was the representation of the data and knowledge acquired according to the RBS methodology. First of all, the information about of HSCWs was organized in 37 decision trees and one matrix. Then it was simply converted into IF-THEN rules by traversing each branch from the root to the leaf or crossing from the columns to the rows (4.4. Model implementation and integration).

An important step in the development of EDSS-maintenance prototype was the evaluation process which aims to verify whether we have built the system "*right*" and validate whether we have built the "*right*" system. To perform this evaluation we proposed a methodology based on four steps: (1) verification, (2) laboratory validation with historical data, (3) laboratory validation with experts and (4) field validation, which includes two mathematical functions to quantify how accurate is the EDSS (4.5. Evaluation process).

Along with the development of the EDSS-maintenance prototype several recommendations to develop the full EDSS-maintenance were made. These suggestions are based on the modifications of the five-step methodology and the experience gained during the development of the EDSS-maintenance prototype. The first objective of these recommendations is to improve data and knowledge acquisition (quantity and quality). Afterwards these recommendations are focused on the analysis and representation phase of this knowledge, and finally they conclude with some advice for the EDSS-maintenance evaluation step.

The operation of the EDSS-maintenance prototype developed is also presented and an example of operation and maintenance protocol for a particular HSCW is provided in order to illustrate the capabilities of the EDSS-maintenance prototype (5. EDSS-maintenance prototype operation).

Finally, the main conclusions derived from this thesis are enumerated and some challenges to be solved in a near future are presented in chapter 6 (6. Conclusions).

Preface

The Laboratory of Chemical and Environmental Engineering (LEQUIA, from *Laboratori d'Enginyeria Quimica i Ambiental*, in Catalan) of the University of Girona (UdG, from *Universitat de Girona*) started the research around the application of Environmental Decision Support Systems (EDSSs) in small Wastewater Treatment Plants (WWTPs) in 2001, when the Catalan Water Agency (*Agència Catalana de l'Aigua*) set up the urban wastewater collection and treatment programme (PSARU 2002, from *Programa de Sanejament d'Aigües Residuals Urbanes 2002*, in Catalan – Code: L01/01 PSARU). Since then and in cooperative research with the Knowledge Engineering and Machine Learning Group (KMLG) from the Technical University of Catalonia, the Soil Science Laboratory from the University of Barcelona and the Cemagref from Lyon further research have been done in the application of EDSS within the small WWTP framework, mainly the following two projects:

- *Lagune naturel, infiltration-percolation et lits de traitement de boues plantés de roseaux: procédé de traitement des eaux pluviales, les eaux usées domestiques et boues primaires* (Waste stabilization pond, intermittent sand filters and constructed wetlands to treat sludge: runoff, urban wastewater and primary sludge treatment). European Project – Code: LIFE02 ENV/F/000303.

- *Sistema de suport a la decisió per a l'establiment de protocols d'explotació a les depuradores del PSARU 2002* (Decision support system for the adequate definition of exploitation protocols for the WWTP planned within the PSARU 2002). Catalan Water Agency Project – Code: L02/03 PSARU Manteniment.

Most of the PhD work of the candidate Clàudia Turon Planella has been framed within the L02/03 PSARU Manteniment project, however she has also been fully involved in the L01/01 PSARU and LIFE02 ENV/F/000303 projects. The research work carried out within these projects has enabled to produce several communications and publications. Most of the work presented in international conferences and/or in journal publications is compiled within the PhD document while others have become the groundwork needed to develop the thesis. All of them listed below.

- **Related to the L01/01 PSARU project:**

  - Alemany J., Comas J., **Turon C.**, Ribas A., Bou J., Coscolluela S. and Poch M., 2004. Participation of stakeholders during the development of an EDSS to assess decision in the small communities wastewater plan in Catalonia. In proceedings of the *IFAC Workshop, Venice, Italy.*

  - **Turon C.**, Alemany J., Poch M., Cortés U. and Bou J., 2004. An environmental decision support system to identify the most appropriate wastewater treatment process. From Catalonia to Latin America. *Research on Computer Science. e-Environment Progress and Challenge*, 11, 15-30.

  - Alemany J., Comas J., **Turon C.**, Balaguer M.D., Poch M., Puig M.A. and Bou Josep, 2005. Evaluating the application of a decision support system in identifying adequate wastewater treatment for small communities. A case study: the Fluvià River Basin. *Water Science and Technology,* 51 (10), 179-186.

- **Related to the L02/03 PSARU Manteniment project:**

  - **Turon C.**, Poch M. and Cortés U., 2004. A methodology for knowledge reuse: Application in the automatic generation of operational protocols for wastewater treatment plants. Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E. and Jakeman, A.J. (eds). *Complexity and Integrated Management Transactions of the 2nd Biennial Meeting of the International Modelling and Software Society,* 3, 1099-1104, iEMSs: Manno, Switzerland.

  - **Turon C.**, Comas J., Alemany J., Bou J. and Poch M., 2004. Development of an EDSS for the optimal maintenance of stabilization ponds. Application to tackle the odour and water colour problems. In proceedings of *6th International Conference on Waste Stabilization Ponds,* vol. Waste Stabilization Ponds, 423-431, September 2004, Avignon, France.

  - **Turon C.**, Alemany J., Bou J., Comas J. and Poch M., 2005. Optimal maintenance of constructed wetlands using an environmental decision support system. *Water Science and Technology,* 51 (10), 109-117.

  - **Turon C.**, Comas J., Molle P., Torrens A. and Poch M., 2006. Expert validation of an EDSS for optimum constructed wetlands maintenance. In proceedings of the *7th International Conference on Small Water and Wastewater Systems,* March 2006, Mexico DF, Mexico.

  - **Turon C.**, Comas J., Cortés U. and Poch M., 2006. Confronting EDSS-maintenance validation. In proceedings of the *Summit on Environmental Modelling and Software 3rd Biennial meeting of the International Environmental Modelling and Software Society.* Voinov A., Jakeman A.J., Rizzoli A.E. (eds). July 2006, Burlington, USA. CD ROM. Internet: http://www.iemss.org/iemss2006/sessions/all.html

  - **Turon C.**, Comas J., Cortés U. and Poch M., 2006. Development of an EDSS to prevent, identify and solve wastewater treatment plant problems. Case study: Waste stabilization ponds. In proceedings of *5th European Conference on Artificial Inteligence* (ECAI) workshop on *Binding Environmental Sciences and Artificial Intelligence* (BESAI). Oprea, M., Sànchez-Marrè, M., and Wotawa, F. (eds.). 28 August – 1 September 2006, Riva del Garda, Italy.

  - Velayos G., **Turon C.**, Comas J. and Poch M., 2006. Experience on constructed wetlands in Catalonia – State of the art. In proceedings of the *10th International Conference on Wetlands Systems for Water Pollution Control,* September 2006, Lisbon, Portugal (under revision to be published in *Water Science and Technology*).

  - **Turon C.**, Comas J., Dalmau J., Rodríguez-Roda I., Alemany J. and Poch M., 2006. Decision support for the wastewater treatment domain: Successful case studies for planning, maintenance, operation and control. In proceedings of the *1st Mediterranean Congress on Chemical Engineering for Environment,* October 2006, Venice, Italy (under revision to be published in *Industrial and Engineering Chemistry Research*).

  - **Turon C.**, Comas J., Alemany J. and Poch M. (2006). Environmental decision support systems: A new approach to support the operation and maintenance of constructed wetlands. *Ecological Engineering* (submitted).

  - **Turon C.**, Comas J., Alemany J., Bou J. and Poch M. (2006). EDSS-maintenance: A tool to support operation and maintenance of waste stabilization ponds. *Journal of Environmental Engineering* (submitted).

Nowadays we are preparing a paper which summarizes the experience acquired developing the EDSS to support the definition of operation and maintenance protocols for small WWTP (L02/03 PSARU Manteniment project), for the *Water Research* journal.

- **Related to the LIFE02 ENV/F/000303 project:**
  - Comas J., **Turon C.**, Torrens A., Poch M. and Molle P., 2006. Development of an EDSS to improve the intermittent sand filters design. In proceedings of *7th International Conference on Small Water and Wastewater Systems,* March 2006, Mexico DF, Mexico (under revision to be published in *Water Science and Technology*).

Besides, Clàudia Turon Planella is co-editor of the online book: *Gestió i tractament d'aigües residuals*, Balaguer M.D., Puig M.A., Salgot M., Sànchez-Marré M. and Turon C., edited by the University of Girona (http://www.udg.es/publicacions_factoria/xarxa_tematica/presentacio.html).

On the other hand, the training of Clàudia Turon Planella has been complemented with two research stays carried out during her PhD student period. The first one was a short stage of one week (9 to 12 March 2004) at the Cemagref (Lyon) to share experiences with Mrs. Catherine Boutin, Dr. Pascal Molle and Mr. Pierre-Henry Doudane, while the other one was a 3-month stay at the Model-based Systems and Qualitative Reasoning Group (MQM) research group of the Technical University of Munich, in Munich (Germany) under the supervision of Professor Peter Struss (5th September – 11th December 2005).

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Acronyms and abbreviations

AI: Artificial Intelligence

ASM: Activated Sludge Model

BAT: Best Available Technologies

BOD: Biological Oxygen Demand

CBS: Case Based System

COD: Chemical Oxygen Demand

DO: Dissolved Oxygen

EDSS: Environmental Decision Support System

HMM: Hidden Markov Model

HSCW: Horizontal Subsurface Constructed Wetland

KDD: Knowledge Discovery in Databases

PE: Population Equivalent

PLC: Programmable Logic Controller

PMARU: PSARU 2002 wastewater treatment plants maintenance program
(*Programa de manteniment per a les estacions depuradores del PSARU 2002,* in Catalan)

PSARU: Urban wastewater collection and treatment program
(*Programa de sanejament d'aigües residuals urbanes*, in Catalan)

PVC: Polyvinyl Chloride

RAS: Return Activated Sludge

RBS: Rule Base System

SCADA: Supervisory Control And Data Acquisition

SS: Suspended Solids

UV: Ultra Violet

WAS: Wasted Activated Sludge

WWTP: Wastewater Treatment Plant

1. Introduction

1. Introduction

The increasing rhythm of industrialization, urbanization and population growth that our planet has faced for the last few hundred years has forced society to consider whether human beings are changing the conditions that are essential to life on Earth. Environmental pollution and habitat destruction/fragmentation negatively affect the quality of water, air and soil, and hence plant, animal and human life [Sydow *et al.* (1998) and El-Swaify and Yakowitz (1998)]. This increasing degradation of the environment has forced society to consider changes in human behaviour to ensure the essential conditions for life on Earth [Comas (2000)].

In this sense, wastewater treatment has become one of the most important environmental issues because wastewater treatment is fundamental to keep and increase the quality of the water natural resources (rivers, lakes, aquifers and seas). The European Directive 91/271 establishes that every European city or village with a population larger than 2,000 Population Equivalent (PE) must treat its wastewater before the year 2005, at least reducing the Suspended Solids (SS), the Biological Oxygen Demand (BOD) and the Chemical Oxygen Demand (COD) contained in the wastewater. Besides, this directive specifies that the communities with fewer than 2,000 PE must provide an adequate wastewater treatment before the 31 December 2005. The European Directive 2000/60 extended this last deadline until December 2015.

The correct management of these wastewater treatment facilities has become very important, not only because of more and more restrictive environmental and social regulations but also for economic reasons. The complexity associated with Wastewater Treatment Plant (WWTP) management (1.1. Wastewater treatment plants (WWTPs)) led to the need for new tools (1.2. Environmental decision support systems (EDSSs)). Although several attempts have been made to apply these new tools in medium and large scale WWTP management, few advances have been made in small WWTPs (1.3. WWTP and EDSS, a new approach).

1.1. Wastewater treatment plants (WWTPs)

A WWTP can be defined as an industrial facility which receives wastewater (and sometimes runoff) from domestic and/or industrial sources, and through a combination of physical, chemical and biological processes reduces (treats) the wastewater to less harmful by-products.

The interactions among physical, chemical and biological processes convert WWTPs to complex systems whose management requires multi-disciplinary approaches and expertise from different social, technical and scientific fields. Other special features of WWTP that makes them more complex systems can be depicted from the description of environmental systems made by Guariso and Werthner (1989):

- **Ill-structured domain:** Wastewater treatment systems are poorly or ill-structured domains. Their management involves expert knowledge which makes the domain characterization in terms of mathematical theory or deterministic models whose properties are well understood difficult. The WWTP experts possess this heuristic knowledge, which represents:
    - The subjective decision-making exhibited by experienced engineers when meeting the requirements of a given process.

- A way of combining different kinds of information that cannot be expressed with mathematical modelling.

- **Intrinsic unsteadiness:** Most of the chemical and physical properties as well as the population of microorganisms (both in total quantity and number of species) involved in WWTP processes do not remain constant; on the contrary, they evolve over time.

- **Uncertainty and imprecision of data or approximate knowledge and vagueness:** The parameters used in models defining WWTP processes are usually uncertain and their operational ranges are only approximations. People use linguistic qualifiers for concepts or values that are difficult to capture and represent [Beltramini and Motard (1988)]. Part of the information available in WWTPs is qualitative and difficult to translate into numerical values.

- **Huge quantity of data and knowledge:** Information technology is now a mature and pervasive technology. Most WWTPs have several computers installed (mainly SCADAs and PLCs). These computers have led to a significant increase in the amount of data. However, such an increase in frequency, quality, quantity or diversification of process data not always corresponds to a similar increase in the process understanding and improvement [Olson *et al.* (2003)].

- **Heterogeneity and scale:** Since the media in which environmental processes take place are not homogeneous and cannot be easily characterised by measurable parameters, the data is often heterogeneous. In WWTPs data (1) can come from different sources (on-line quantitative, off-line quantitative, qualitative observations of plant operators and microscopic observations), (2) have different formats and (3) correspond to measures with different time-scales due to the different frequency of analysis and the time that these measures take.

Moreover, WWTP have additional particular features from the standpoint of automatic control that make them even more difficult to control and supervise using a single conventional control strategy:

- **Non-linearity:** The reactions of WWTP processes often reach pseudo-stability when substrates, nutrients or oxygen are limited. The system remains in the non-linear operation state, which is often represented by the Monod equation, and this makes the application of modern controls more difficult.

- There is a **lack or paucity of knowledge** with respect to the understanding of the process mechanisms and, thus, a large dependence on empirical knowledge: detailed knowledge of the wastewater treatment process is still limited and theoretical understanding of biological phenomena such as clogging in constructed wetlands, bloom algae in waste stabilization ponds, etc. is poor. Therefore WWTP operators usually rely on their empirical know-how to solve problems.

- **There is a need to always fulfil the effluent specifications** to minimise the impact over the receiving media.

- **Change in control objective:** Usually the control objective of a wastewater treatment facility is treatment efficiency from the standpoint of effluent water quality but it may change under some special conditions such as episodes of stormy weather or the inhibition of biological activity.

- **Trends of variables:** The trend of some key variables (rather than punctual values) is becoming increasingly important to extract more information about the state of the process.

In the last decades, mathematical and statistical models, numerical algorithms and computer simulations have been used as the means to gain insight into some environmental problems and to provide useful information to decision makers [Poch *et al.* (2004)]. However, the complexity of wastewater treatment systems require other approaches than a straightforward application of conventional numerical models to look for optimal management when (1) the process state of the WWTP is far from its normal operation and (2) reasoning with qualitative information is essential to deal with problems.

1.2. Environmental decision support systems (EDSSs)

The effort to integrate different tools to deal with complex systems has led to the development of the so-called Environmental Decision Support Systems (EDSS) in the late 80's [Guariso and Werthner (1989) and Rizzoli and Young (1997)]. An EDSS can be defined as an interactive, flexible and adaptable software, which can link numerical models/algorithms with knowledge-based techniques, geographical information systems and environmental ontologies (Figure 1.1), and that have been developed for supporting environmental decision makers in choosing between alternatives. EDSSs incorporate an explicit decision procedure based on a set of theoretical principles that justify the "rationality" of this procedure [Fox and Das (2000)]. Moreover, EDSSs reduce the time in which decisions are made in an environmental domain, and improve the consistency and quality of those decisions [Haagsma and Johanns (1994), Comas (2000) and Cortés *et al.* (2001)].

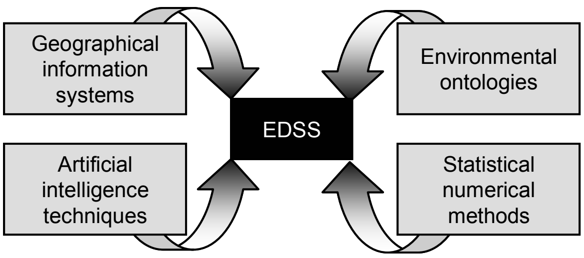

Figure 1.1. EDSS conceptual components [modified from Poch *et al.* (2004)].

The range of environmental problems to which EDSSs have been applied is wide and varied (i.e. water management, agriculture production, land management, air quality improvement, forest management, etc.). All these environmental problems correspond to complex systems in which (1) the existent uncertainty does not allow the use of simple models and (2) expert knowledge is crucial to providing satisfactory proposals.

How one of these EDSSs is constructed will vary depending on the type of environmental problem and the type of data and knowledge that can be acquired [Cortés *et al.* (2000)]. Although there are no clear guidelines on how develop these decision support tools, several similarities have been found in some of the EDSSs developed previously [Silvert (1994), Miyamoto *et al.* (1996), Haastrup *et al.* (1998), Seder *et al.* (2000), Geng *et al.* (2001) and Cheng *et al.* (2003)]: following analysis of the information available for solving a problem, a set of models are selected to represent these data and knowledge (Figure 1.1). The use of Artificial Intelligence (AI) tools and models provides direct access to expertise, and their flexibility make EDSSs capable of supporting learning and decision making processes. Their integration with numerical and/or statistical models in a single system provides higher accuracy, reliability and utility [Cortés *et al.* (2000)]. This confers EDSSs the ability to confront complex problems, in which the experience of experts provide valuable help for finding a solution to the problem [Poch *et al.* (2004)].

It was also possible to identify the main components of an EDSS from the EDSSs previously developed:

a) Knowledge base: A knowledge base is a special kind of database for knowledge management. It stores knowledge in a computer-readable form, usually for the purpose of having automated deductive reasoning applied to it. It contains a set of data, often in the form of rules that describe the knowledge in a logically consistent manner. Logical operators such as *And* (conjunction), *Or* (disjunction), material implication and negation may be used to build it up from the atomic knowledge. Consequently classical deduction can be used to reason about the knowledge in the knowledge base. Determining what type of information is captured, and where that information resides in a knowledge base is something that is determined by the processes that support the system. A robust process structure is the backbone of any successful knowledge base.

b) Inference engine: The inference engine is the generic control mechanism that applies the axiomatic knowledge present in the knowledge base to the task-specific data to arrive at some conclusion. This is the second key component of all decision support systems. Having a knowledge base alone is not of much use if there are no facilities for navigating through and manipulating the knowledge to deduce something from it.

c) Interfaces: A user interface is the meeting point between a computer and someone using the EDSS. The interfaces allow the introduction of input data, the control of the EDSS device and to provide proposals (the conclusions of the EDSS reasoning process).

Therefore, to develop an EDSS it is necessary (Figure 1.2): (a) to define the environmental problem to be solved, (b) to acquire the information that permits the definition of a solution, (c) to select a model to represent this information and (d) to choose software to codify this knowledge in a machine-processable format and derive a solution from the knowledge base. Last but not least, to make the EDSS a user-friendly tool it is necessary (e) to create the user interfaces.

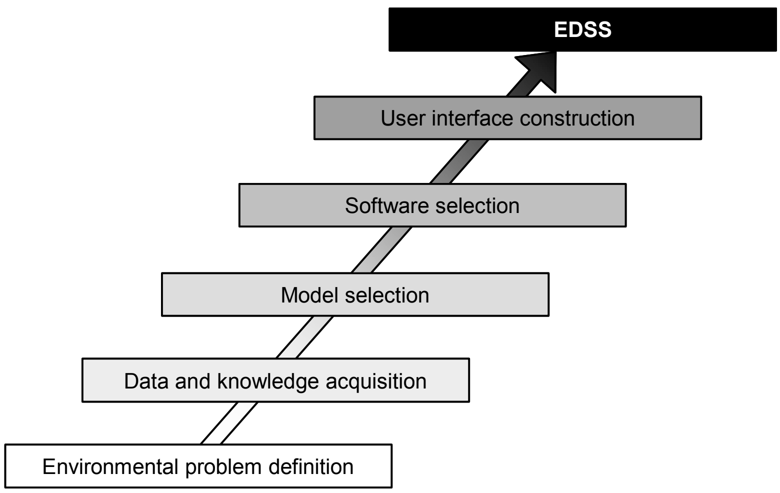

Figure 1.2. Methodology to develop an EDSS.

1.3. WWTP and EDSS, a new approach

During the last twenty years, several EDSSs approaches have been developed within WWTP framework to support: (1) the selection of the most appropriate technology [Okubo *et al.* (1994), Chin-Tien and Jehng-Jung (1996), Balkema *et al.* (2001), Comas *et al.* (2003, a) and Adenso-Diaz *et al.* (2005)]; (2) the design of the WWTP facilities [Geselbracht *et al.* (1986), Krovvidy *et al.* (1991), Krovvidy and Wee (1993), Hudson *et al.* (1997), Sairan *et al.* (2005) and Comas *et al.* (2006)]; and (3) WWTP management at the top [Ladiges and Kayser (1993), Serra *et al.* (1993), Ozgur and Stenstrom (1994), Berg and Olsson (1996), Zhu and Simpson (1996), Wen and Vassiliadis (1998), Baeza *et al.* (2000), Flores *et al.* (2000), Puñal *et al.* (2000), Clausson-kass *et al.* (2001), Baeza *et al.* (2002), Holubar *et al.* (2002), Rodríguez-Roda *et al.* (2002), Comas *et al.* (2003, b), Olsson *et al.* (2003), Lee and Scholz (2006), Martinez (2006), Rodríguez-Roda *et al.* (2006) and Xu *et al.* (2006)]. Most of these EDSSs have been developed to support the management of high-loaded WWTPs based on activated sludge technology (pilot plants or full scale facilities). We have only found one EDSS supporting the management of WWTPs based on low-loaded technologies. This EDSS predicts if the outflow BOD and SS concentrations of a vertical flow constructed wetland are above or below the thresholds set for water quality [Lee and Scholz (2006)].

The first EDSS approaches to WWTP management [i.e. Ladiges and Kayser (1993) and Berg and Olsson (1996)] never really succeeded and were not tested on real facilities mainly because they were too complex and experienced some difficulties capturing all the available knowledge in reliable models and advisory systems [Olson *et al.* (1998)]. The more recently developed WWTP-management EDSSs have been implemented and evaluated in real WWTPs [i.e. Wen and Vassiliadis (1998), Puñal *et al.* (2000), Rodríguez-Roda *et al.* (2002) and Martínez (2006)]. The successful results obtained from these approaches have generated high expectations for EDSSs as tools to tackle the complexity associated with WWTP management mainly because they:

- Manage huge volumes of data.
- Handle expert knowledge.
- Tackle the uncertainty of data and knowledge.
- Integrate both data and knowledge, through different models, into a software.
- Accurately evaluate multiple alternatives.
- Diagnose an abnormal situation and propose a therapy to solve this problematic event.
- Provide objective offline/online proposals.

Since the optimal WWTP management is concerned with trying to obtain good wastewater treatment efficiency and to maintain the maximum process stability, both operation and maintenance activities are required to avoid operational problems:

- **WWTP operation:** Set of controls or measures carried out to evaluate the performance state of the WWTP and to detect possible deviations or problematic situations. The adjustments of the equipments (i.e. the set-point of the dissolved oxygen) can also be included in the WWTP operation.
- **WWTP maintenance:** Set of actions to refine the process equipment upon failure (corrective) or to refurbish and renew the equipment to prevent failure (scheduled).

From the definition of these management processes it is possible to deduce that operation measures and maintenance actions vary from one WWTP to another because the equipment composing the facilities, the performance of the depuration processes, the problematic situations, etc. differ among WWTPs, even when the wastewater treatment technology is the same. This fact increases the complexity described for the WWTP management and limits the reutilization of the developed EDSSs to support the operation and maintenance.

The present thesis tries to face the complexity associated to the small WWTP management by means of an EDSS which supports the definition of operation and maintenance protocols (2. Objectives). Hence, after the presentation of a methodology to build EDSSs (3. Methodology for developing an EDSS), the development of the EDSS is detailed (4. Development of the EDSS-maintenance prototype). An example of the operation and maintenance protocol is provided and discussed in chapter 5 to illustrate the capabilities of this EDSS (5. EDSS-maintenance prototype operation). Finally, the conclusions of the thesis and some future work proposals are provided (6. Conclusions).

2. Objectives

2. Objectives

When the urban wastewater collection and treatment programme (PSARU 2002, from *Programa de Sanejament d'Aigües Residuals Urbanes – 2002*, in Catalan) ended in 2002, the Catalan Water Agency had to define operation and maintenance protocols for the small WWTPs involved in this sanitation programme. The complexity associated with the definition of these protocols aroused the necessity to develop an EDSS. Therefore, the Catalan Water Agency set up the project "Decision support system for the definition of operation and maintenance protocols for WWTPs involved in PSARU 2002" (*Sistema de support a la decisió per a l'establiment de protocols d'explotació a les depuradores del PSARU 2002*, in Catalan). This project was called PMARU, and the EDSS developed within this framework was named EDSS-maintenance.

The present thesis, developed within the PMARU project framework, aims to develop an EDSS-maintenance prototype. Among the sanitation alternatives proposed in the PSARU 2002 project both high-loaded and low-loaded technologies can be found, being constructed wetlands the most recommended treatment alternative. Hence, the general objective of this thesis is to develop a prototype of the EDSS-maintenance to support the definition of operation and maintenance protocols for constructed wetlands, specifically Horizontal Subsurface Constructed Wetlands (HSCWs). This prototype will become the required groundwork to develop the full EDSS to cover all types of WWTPs. To achieve this main objective, especial features for the development methodology and the EDSS-maintenance prototype itself must be considered:

1) The methodology has to be able to confront the complexity associated with the definition of operation and maintenance protocols for HSCWs.

2) The application of the methodology must provide an EDSS sound and realistic.

3) The appliance of the EDSS-maintenance prototype into full-scale facilities must be feasible, protocols must be easy to understand and they have to provide useful information in terms of prevention, identification and solution of HSCW problems.

4) The EDSS-maintenance prototype to be developed must be easily extended to the other wastewater treatment technologies involved in the PSARU 2002 project.

Hence, the development of the EDSS-maintenance prototype involves the following sub-objectives:

a) The selection of the most appropriate methodology to develop the EDSS (3. Methodology to develop an EDSS).

b) The application of this methodology to develop EDSS-maintenance prototype (4. Development of EDSS-maintenance).

This two-step procedure must be conducted whilst bearing in mind the purpose of full EDSS-maintenance.

3. Methodology for developing an EDSS

3. Methodology for developing an EDSS

Although there is not a unique methodology to develop an EDSS, some similarities have been found in EDSSs developed previously: following analysis of the information available for solving a problem, a set of models are selected to represent these data and knowledge (Figure 1.1). In this respect Poch *et al.* (2004) propose a methodology based on the following steps (Figure 3.1):

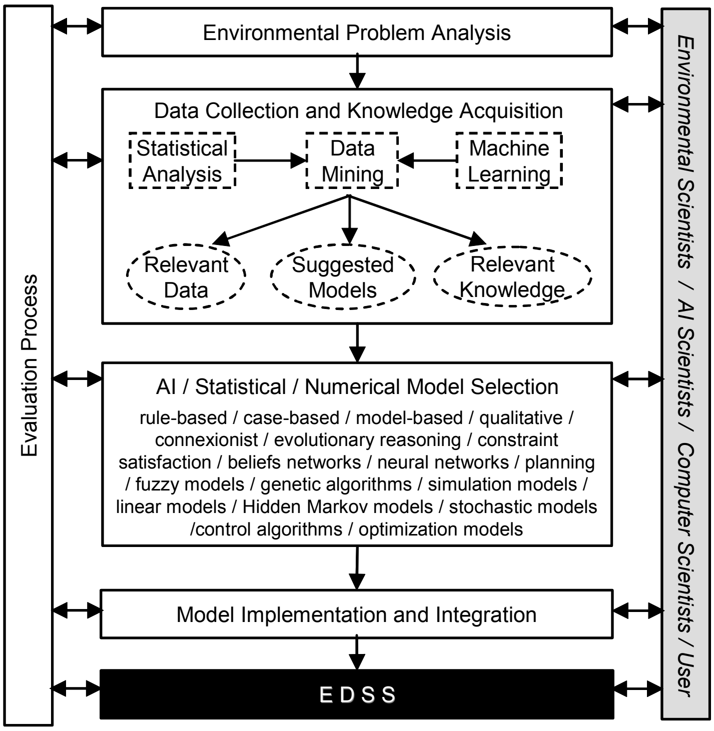

Figure 3.1. Development of an EDSS [modified from Cortés *et al.* (2000)].

3.1. Environmental problem analysis

The environmental problem must be defined in the first step. This definition is based on the characterization of the domain, the study of the background and the current state of the problem. This analysis allows both (1) definition of the objective of the EDSS and (2) identification of what is required to solve the environmental problem.

3.2. Data collection and knowledge acquisition

Once the environmental problem analysis is finished, the data collection and knowledge acquisition phase begins. This stage involves the acquisition and analysis of the data and knowledge in order to then propose a range of problem solutions.

3.2.1. Data and knowledge acquisition

Data and knowledge required to identify and solve the environmental problem can be acquired from different sources (Figure 3.2): technical and scientific literature, site visits and expert interviews, and historical databases. This ensures that empirical, theoretical and historical information will be included within the knowledge base. The consultation of different sources facilitates the integration of a plurality of views, perspectives and goals from all of the disciplines involved in resolving the environmental problem [Turon *et al*. (2004)].

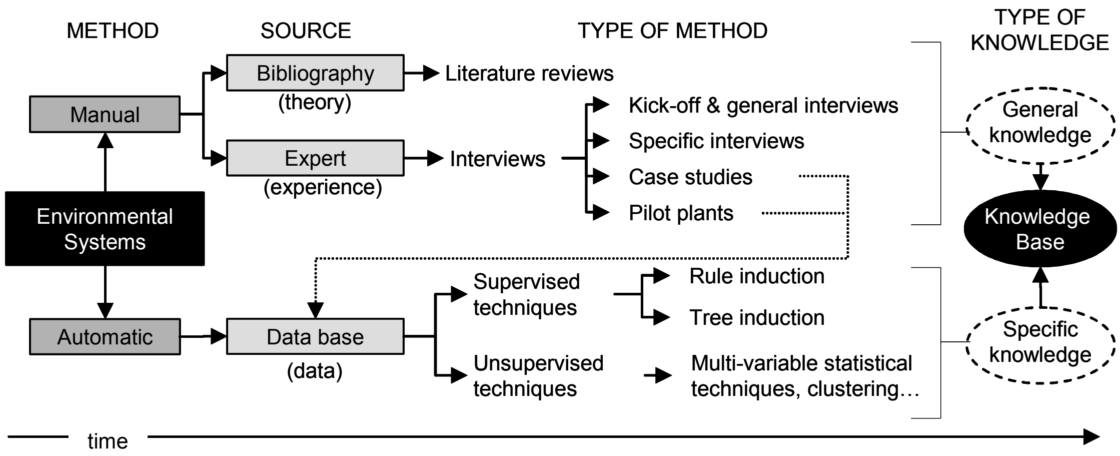

Figure 3.2. Classification of the sources and methods used for knowledge acquisition in environmental systems [modified from Comas (2000)].

3.2.2. Data and knowledge analysis

The second step involves analysis of the acquired data and knowledge generally by means of data mining techniques (both statistical analysis and machine learning techniques) to establish relationships and identify patterns. Data mining is one particular step in the whole process of extracting knowledge from databases. Fayyad *et al.* (1996) defined Knowledge Discovery in Databases (KDD) as a nontrivial process of identifying valid, novel, potentially useful, and ultimately understandable patterns in data:

- ***Nontrivial*** means that the process goes beyond computing closed-form quantities; that is, it must involve some search or inference for structure, models, patterns or parameters. It is not a straightforward computation of predefined quantities like computing the average value of a set of numbers.

- ***Data*** is a set of facts and ***pattern*** is an expression in some language describing a subset of the data or a model applicable to the subset.

- The term ***process*** implies that KDD comprises many steps, which involve (Figure 3.3):

  - <u>Selection, Pre-processing and Transformed Data:</u> Data preparation and cleaning is often neglected although it is an extremely important step in the KDD process. This step involves everything from comprehension of the domain to obtaining transformed data:

    a) The starting point in the KDD process is developing an understanding of the application domain and relevant prior knowledge, as well as identifying the aim of the KDD process.

    b) The second stage is to create a target data set on which to work.

    c) The third stage is data cleaning and pre-processing: removing noise, collecting the necessary information to model or account for noise, deciding on strategies for handling missing data and accounting for time-sequence information and known changes.

d) The final sub-step is data reduction and projection. This involves finding useful features to represent data and using dimensionality reduction or transformation methods to reduce the effective number of variables under consideration or to find invariant representations for the data.

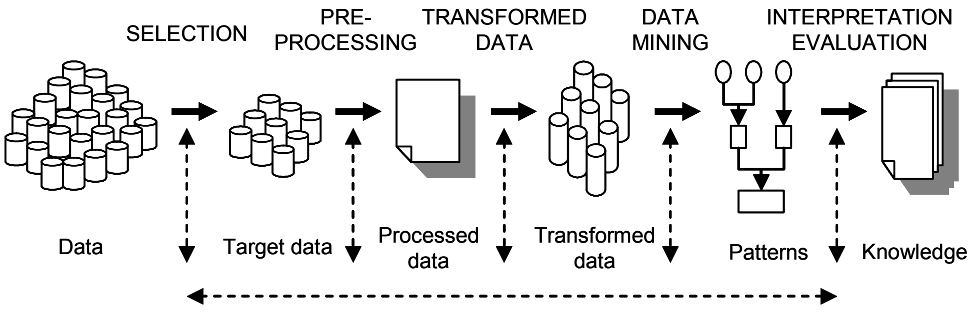

Figure 3.3. An overview of the steps that compose the KDD process [Fayyad *et al.* (1996)].

- Data mining: The second step is the core of the KDD process and is based on the application of specific data-mining methods for fitting models to or determining patterns from data. Naturally, it is not possible to detail all data mining tools here, hence only the most common and useful data mining techniques are presented [Spate *et al.* (2006)]:

a) Clustering: Clustering techniques are used to divide a data set into groups, each of which includes similar data records. These are suitable for discovering the underlying structure of the target domain, if this is unknown. For this reason, they belong to the group of techniques known as unsupervised learners.

A variety of algorithms can be used for clustering, but they all share the property of iteratively assigning data records to a cluster, calculating a measure (usually similarity), and re-assigning records to clusters until the calculated measures show little change, indicating that the process has converged to stable segments. Data records within a cluster have more similarities to another and more differences from data records in other clusters.

b) Classification: Classification techniques are used to group data into segments called classes. This process requires that the end-user / analyst know ahead of time how classes are defined. Thus classification belongs to the supervised learning methods.

Classification routines in data mining can use a variety of algorithms and which particular algorithm is used affects the way data records are classified. A common approach for classifiers is to use decision trees for partition and segment records. New data records can be classified by traversing the tree from the root through branches and nodes to a leaf representing a class. The path a record takes through a decision tree can then be represented as a rule.

- Interpretation and evaluation: The third step consists in interpreting and evaluating mined patterns. This step involves visualization of the extracted patterns and models and/or visualization of the data provided by the extracted models.

- Refinement: The KDD process can involve significant iteration and can contain loops between two steps.

The results of this analysis allow (1) the construction of models for the processes involved in the environmental problem, (2) obtaining the correlation among the variables involved and (3) identifying relevant data and knowledge [Torasso and Portinale (1997), Hernandez and Serrano (2001) and Cortés *et al.* (2003)].

3.3. Model selection

The next step consists in selecting the set of models that best cover all kinds of knowledge and functionalities required for the decision-making processes. This applies not only to numerical and statistical models, but also to AI methodologies (Figure 3.1):

3.3.1. Numerical models

A numerical model is a model that uses one or more mathematical expressions to approximate the behaviour of a system. There are two types of numerical models:

- **Deterministic models:** Deterministic models are mathematical models aimed at describing some or all of the biological or physical-chemical processes that take place within an environmental system. **Stochastic models** are an example of a deterministic model. Since *stochastic* means to vary over time, a stochastic model can be defined as a model of a system that includes some sort of random variable or variables. Stochastic models are used to simulate deterministic systems which include smaller-scale phenomena that cannot be accurately observed or modelled. Based on a set of random outcomes, the experience of experts is projected and the outcome is noted. Then this is repeated with a new set of random variables. After several repetitions, a distribution of outcomes is provided showing the most likely estimate.

- **Empirical models:** An empirical model is used when the knowledge available is insufficient to characterise a system or phenomenon. The model equations (and parameters) are constructed based on the experience of experimenting with the system or phenomenon (e.g. using historical databases, data-driven models). **Neural networks** are typical data-driven models: Artificial neural networks are made up of interconnecting artificial neurons designed to model (or mimic) some properties of biological neural networks. The artificial neuron is analogous to the biological neuron and performs the following functions[Turban (1992)]:

  1) It receives inputs (each input corresponds to a single attribute) analogous to electrochemical impulses that biological neurons receive.

  2) It weights inputs to express the relative importance of each attribute at the artificial neuron.

  3) It finds the weighted average of all the input elements to each artificial neuron by means of a summation function that multiplies each input value (X_i) by its weight (W_i) and totals them together for a weighted sum Y.

$$Y = \sum_i^n X_i \cdot W_i$$

  4) It transforms the summation function value into an internal stimulation which may or may not produce an output.

5) The output can be the input of an interconnected artificial neuron or can be the final solution of the neural network: the solution to a problem.

Well-designed neural networks are trainable systems that can often "learn" to solve complex problems from a set of examplars and generalize the "acquired knowledge" to solve unforeseen problems.

3.3.2. Statistical models

Statistical models include issues such as statistical characterization of numerical data, estimating the probabilistic future behaviour of a system based on past behaviour, extrapolation or interpolation of data based on some best-fit, error estimates of observations, or spectral analysis of data or model generated output. There are different statistical models, such as:

- **Lineal models:** In statistics the lineal model is given by the equation:

$$Y = X\beta + \alpha$$

Where *Y* is an *n* rows per *1* column vector of random variables, *X* is an *n x p* matrix of known quantities (observable and non-random), whose rows correspond to statistical units, β is a *p x 1* vector of parameters (unobservable), and α is an *n x 1* vector of errors, which are uncorrelated random variables each with expected value 0 and variance σ^2. Having observed the values of *X* and *Y*, the statistician must estimate β and σ^2.

- **Hidden Markov model:** A Hidden Markov Model (HMM) is a statistical model where the system being modelled is assumed to be a Markov process with unknown parameters, and the challenge is to determine the hidden parameters from the observable parameters. The extracted model parameters can then be used to perform further analysis, for example for pattern recognition applications. In a regular Markov model, the state is directly visible to the observer, and therefore the state transition probabilities are the only parameters. In a HMM, the state is not directly visible, but variables influenced by the state are visible. Each state has a probability distribution over the possible output tokens. Therefore the sequence of tokens generated by an HMM gives some information about the sequence of states. HMMs are especially known for their application in speech recognition and biological sequence analysis (bioinformatics) [Rabiner and Juang (1986)].

3.3.3. Artificial intelligence models

AI provides techniques for developing computer programs which are able to carry out a variety of tasks through simulation of the human intelligent in problem solving. Since every domain is different, AI provides a set of different techniques [Krishnamoorthy and Rajeev (1996)], such as:

- **Rule-based model:** The simplest form of AI is the Rule-Based System (RBS), also known as *expert system*. RBSs are based on rule-based models which represent knowledge in terms of heuristic rules. Each rule has a left hand side (IF <condition>) and a ride hand side (THEN <conclude>). The RBS process begins with the examination of rule conditions, which contain information about certain facts which must be true in order for the rule to potentially fire (that is, execute). When a rule is fired, any actions or conclusions specified in its THEN clause (right hand part) are provided by the RBS. RBS are usually used when the expert knowledge is general [Turban (1992) and Jackson (1999)].

- **Case-based model:** The Case-Based System (CBS) is a form of AI-based decision-making which uses previously acquired case experience. CBSs are based on case-based models which describe a complex entity or process by means of cases. A case consists of a problem, its solution and comments on how the solution was derived. CBSs have been formalized as a four-step process: (1) retrieve from memory cases which are relevant to solving the new problem; (2) reuse the solution from the previous case on the new problem. This may involve adapting the solution as needed to fit the new situation; (3) test the new solution in the real world (or a simulation) and, if necessary, review it; (4) retain the solution once it has been successfully adapted to the new problem as a new case in memory. CBSs become specifically useful when knowledge for problem solving is specific [Kolodner (1993), Aamodt and Plaza (1994) and Watson and Marir (1994)].

Once the model is selected, this stage is completed by selecting the most adequate software(s) in terms of (a) the licence cost, (b) its potentialities and (c) the ease of encoding.

3.4. Model implementation and integration

Implementation, understood as the practical encoding of the knowledge according to the model and software selected, entails knowledge representation and codification. The data and knowledge acquired can be represented by means of decision trees, matrices and mathematical equations (algebraic or differential). These data and knowledge then have to be codified according to the software selected to form the knowledge base of the EDSS.

Integration is defined as the process by which the different models used are made into a whole functional and structural EDSS. It can be conducted in parallel when two or more models work simultaneously to obtain a result or in series when the output of one model is the input of the following one.

3.5. Evaluation process

The EDSS must be tested to check its robustness, accuracy, usefulness and usability, both from the user's and scientist's perspective. If there are any faults at any of the development stages, the builders of the EDSS must return to a certain point of the flow diagram in Figure 3.1 and update the required components. When the evaluation phase is completed, the EDSS is ready to be applied to the environmental system.

The evaluation process involves a set of tasks to identify errors or weak points in EDSSs:

- **Verification:** Lack of system specifications and poor understanding of the problem. Moreover, semantic as well as syntactic errors introduced during the implementation which would induce a not sufficiently robust (inconsistent and incomplete) system.
- **Validation:** Erroneous solutions or inability to find any solution to the problem (due to incorrect representation of the domain knowledge), causing inaccuracy.
- **Usefulness:** Unsuitable EDSS efficiency and capabilities (productivity, response time, reliability of the system response, etc.).
- **Usability:** Difficulties for the user to understand and conveniently employ the EDSS (inappropriate interfaces, user load, documentation, etc.).

The proposed evaluation tasks are carried out through a two-stage procedure [Comas (2000)]:

- **Laboratory testing** involves:
  (1) The execution of series of experiments to verify the consistency and completeness of each model.
  (2) Validation with historical or field data to discover inaccuracy and inconsistency of the reasoning modules for each model. If this process is performed comparing the system responses with known results, then it can be done by non-experts of the domain. Otherwise, if the system response can not be compared with known results, then the validation process must be conducted by experts in the domain.
- **Field testing** of the overall EDSS entails the addressing of full-scale situations to detect model integration errors. The flow of information throughout the system is strictly followed to ensure that the system can deal with real qualitative and quantitative variables and missing information and to detect weak reasoning. Once the users employ the EDSS, the usability can be measured objectively and quantitatively by means of functioning errors and productivity, and subjectively through user preferences and interface characteristics. In addition, this field application allows the evaluation of the usefulness by comparing both situations with and without the EDSS.

The evaluation process is no longer thought to be an independent phase in EDSS. This two-stage evaluation procedure occurs iteratively throughout the system development. Results from any stage may necessitate change (reformulations, redesigns, and refinements) in some of the EDSS models. Whenever the system is modified or expanded, it must be re-evaluated.

3.6. Justification of the selected methodology

The methodology proposed by Poch *et al.* (2004) has been successfully applied to develop at least seven EDSS which solve water-related environmental problems:

- **EDSS-Besòs:** Devesa *et al.* (2004) and Devesa (2006) detail the development of an EDSS to manage hydraulic infrastructures and to preserve the quality of water in the Besòs Catchment (in the East of Catalonia). The pilot study considers two sewer systems, their WWTPs, and a stretch of the Congost River. Knowledge required to characterize these three elements was extracted from the literature, historical data and expert interviews. Infoworks CS, GPS-X and Infoworks RS were the software programs chosen to model the three main elements in the study area considered. An RBS representing the operational possibilities for solving typical problems (pick flows, load increases, etc.) is used to offer the decision-maker alternatives. These alternatives are simulated through application of the different models and graphically represented in a GIS (ArcView software). The EDSS-Besòs can operate at two levels:

  (1) To predict future changes in the system in terms of water quality, flow directions, loads, etc. in the light of new infrastructures (i.e. a storage tank) or a new spill into the river.

  (2) To support the more common decisions the River Basin Manager has to make (i.e. to hold certain flow at the storage tank when it rains or to bypass flow from the upstream WWTP to the downstream one).

- **EDSS-STREAMES:** This EDSS is one of the results of the STREAMES (Stream Reach Management, an Expert System – www.streames.org –) an European-funded project (EVK1-2000-00081) which aims to develop an EDSS to support and assess water managers in river quality management, in particular in relation to stream reaches altered by high nutrient loads [Llorens (2004)]. Data and knowledge for the development of EDSS-STREAMES was extracted from literature, site visits, interviews and historical data. This EDSS integrates RBS with GIS to address spatial information for appropriate stream management actions, and a numerical model to estimate point and non-point nutrient sources from middle size catchments. The RBS includes heuristic knowledge from surface water management experts, as well as empirical knowledge from stream scientists. The knowledge was previously organized in decision trees, and then represented and implemented within the EDSS knowledge base to provide three main outputs: diagnoses, cause detection and a list of possible strategies to solve or minimize the problem according to the detected cause/s [Comas *et al.* (2002) and Llorens (2004)].

- **EDSS-control:** Intelligent supervisory system which supports plant operators in the day-to-day operation of large (more that 2,000 PE) WWTPs based on activated sludge technology. The knowledge required to solve this environmental problem was extracted from literature, interviews, and data mining of historical data. All acquired knowledge was structured in an RBS and a CBS. Additionally, a mathematical and deterministic model (ASM model) was used to describe the operational behaviour of these facilities. EDSS-control allows a complete set of operational problems to be detected and solved: foaming, rising, filamentous bulking, under-loading, over-loading, deflocculation (including possible toxic shock), hydraulic shock, mechanical fault, poor primary settler performance, non-biological origin problems on clarifier and influent nitrogen / organic matter shock [Comas (2000), Rodríguez-Roda *et al.* (2002) and Poch *et al.* (2004)].

- **EDSS-treatment:** EDSS-treatment was developed to help water managers to plan adequate wastewater treatment for the communities of fewer than 2,000 PE involved in the PSARU 2002 project. The definition of adequate treatment makes it necessary to combine aspects of small communities and the landscape, the receiving media, and all the available wastewater treatment technologies [Alemany *et al.* (2005)]. This knowledge was extracted from the literature, site visits, interviews and historical data analysis. While expert knowledge was organized into decision trees and matrices, numerical an empirical knowledge regarding investment and operational costs was represented by means of mathematical equations [Comas *et al.* (2003, a)]. This knowledge was then codified using both RBS and numerical models, and was integrated into EDSS-treatment. This decision support system was applied to the 3 800 small communities in Catalonia [Comas *et al.* (2004)]. For each community the EDSS-treatment produced a report containing the following results [Poch *et al.* (2004) and Alemany *et al.* (2005)]: (a) characteristics of the community used by the EDSS-treatment in the reasoning process; (b) list of selected treatments; (c) environmental technical justification for the selected treatments; and (d) economic evaluation of each alternative.

- **EDSS-ISF-design:** Another European Life project (LIFE02 ENV/F/000303) (http://www.eau-barousse.com/projetlife.html) funded the construction of a full-scale WWTP to improve the design and operation of intermittent sand filters treating waste stabilization pond effluents. Data and knowledge acquired during a two-year monitoring program allowed the identification of the reasoning process followed by intermittent sand filter designers as well as the definition of mathematical equations to propose the most appropriate filter configuration according to the influent characteristics and the expected treatment level [Torrens *et al.* (2006)]. This information could not be integrated in only mathematical models since they involve qualitative information and expert reasoning. The experts therefore decided to develop an EDSS. The knowledge for the reasoning process was organized by means of a decision tree and was codified according to the RBS model. Equations describing the intermittent sand filter performance were organized within a mathematical model. Both RBS and a mathematical model were integrated into the EDSS-ISF-design. This knowledge-based system draws out the main intermittent sand filter design characteristics in terms of (1) surface required, (2) type of media (crushed sand, river sand or river sand planted with *Phragmites australis*), and (3) media depth in relation to wastewater characteristics, applied load and required treatment level [Comas *et al.* (2006)].

- **EDSS-INVALL:** Decision support system to enhance the operation of small WWTPs (under 2,000 PE) based on high-loaded technologies. This EDSS was fully integrated into SCADA systems and, is not only responsible for enhancing the main control loops of the activated sludge systems, but also for providing support for solid separation problems. The required knowledge was acquired from three sources (literature revision, site visits and interviews). The EDSS has two models: an RBS and a CBS. The RBS consists of a set of decision trees which are in charge of the main low-level control loops (Dissolved Oxygen (DO), Return Activated Sludge (RAS) and Wasted Activated Sludge (WAS)). The RBS also contains another set of decision trees designed to deal with microbiological problems. The CBS was developed for registering and automatically recovering all the knowledge related to specific problematic episodes [Rodríguez-Roda *et al.* (2006) and Turon *et al.* (2006a)].

- **EDSS-limits:** EDSS to support Catalan Water Agency technicians in authorizing industrial discharges into the sewer systems or into the receiving media: type of pollutants and maximum concentration of these contaminants that can be spilled. The required data and knowledge to develop EDSS-limits was acquired from (1) the literature and reports on Best Available Technologies (BAT); (2) interviews with experts in industrial wastewater management; (3) interviews with Catalan Water Agency technicians currently conducting said authorizations; and (4) with technicians on the receiving media. Moreover, the receiving media information was updated and corroborated with information from on-site visits. Obtained data was organized into matrices and knowledge in decision trees. This information was then codified by means of heuristic rules. Following knowledge implementation, EDSS-limits supports technicians in their definition of the type of pollutants and the maximum concentration allowed in industrial discharges, according to the characteristics of the industry (mainly activity and size) and its location (protection and human pressure of the receiving waters) [Alemany (Oral communication 2006)].

The reasons leading to the construction of EDSS-maintenance by means of the methodology proposed by Poch *et al.* (2004) are:

1) The above seven EDSSs allowed facing water environmental problems which are characterized by:

   - Involving different sectors (i.e. economic, social and ecological). As a consequence, to provide an optimal solution the following are required: (1) the consideration of multiple points of view and (2) the achievement of different purposes.
   - Acquired experiences are crucial in the problem solutions, as well as the need to involve experts in the problem solving processes become essential.
   - Uncertainty associated to these environmental problems cannot be tackled with the traditional tools of mathematical modelling.

2) The environmental problem to be solved by EDSS-maintenance is also a water environmental problem which shares these characteristics.

3) The methodology proposed by Poch *et al.* (2004) provides a certain flexibility to acquire and integrate data and knowledge extracted from different sources and to represent it through of different models (AI, statistical and numerical).

4) This methodology was successfully applied in the construction of seven EDSSs in the water management framework.

4. Development of the EDSS-maintenance prototype

4. Development of the EDSS-maintenance prototype

This chapter can be considered the core of the thesis since it explains how the EDSS-maintenance prototype has been designed and constructed. The development of this EDSS is based on the methodology proposed by Poch *et al.* (2004). However, during the construction of this support tool several modifications were introduced in order to adapt the methodology to our environmental problem. These variations, along with recommendations to build the full EDSS-maintenance, are explained throughout chapter 4.

4.1. Environmental problem analysis

The first step in the development of an EDSS is the analysis of the domain in order to identify and characterize the environmental problem. For this reason, and focusing on the ultimate objective of EDSS-maintenance, the domain analysis started with a study of the current state of wastewater treatment in small Catalan communities. This study allowed the identification and definition of (1) the particularities of the wastewater treatment in small Catalan villages (4.1.1. Wastewater treatment in small communities) and (2) the characteristics of the technologies available to treat wastewater from agglomerations of fewer than 2,000 PE (4.1.2. Wastewater treatment technologies in small communities). Afterwards, and focusing on the objective of the EDSS-maintenance prototype, an in-depth study was conducted on the HSCW technology (4.1.3. Horizontal subsurface constructed wetlands). Finally, using all this information the environmental problem to be solved by the EDSS-maintenance prototype was identified and characterized. This characterization represented fulfilment of the second objective of the environmental problem analysis: identification of what is needed to solve the problem (4.1.4. Requirements to develop EDSS-maintenance prototype).

4.1.1. Wastewater treatment in small communities

A set of laws has been approved by European Union which obliging Member States to comply with certain objectives with respect to wastewater treatment. In order to comply with the European Directive 91/271 and the 19/1991 Law, the *Generalitat de Catalunya* (Catalan Government) approved the *Pla de Sanejament* (Sanitation Plan) on November 7th 1995. This plan was divided into five programmes: (a) the industrial wastewater treatment programme, (b) the urban wastewater treatment programme, (c) the cattle wastewater treatment programme, (d) the agricultural and diffuse wastewater treatment programme, and (e) the sludge treatment programme [Turon *et al.* (2004)].

The urban wastewater treatment programme (*Programa de Sanejament d'Aigües Residuals Urbanes* - PSARU), was divided into two parts. The first one included the definition of WWTPs for communities of over 2,000 PE, representing an increase up to 300 facilities. According to the European Directive 91/271, whenever possible these WWTPs must be based on biological processes. The main technology used for biological wastewater treatment is the activated sludge system. The design and building of this kind of WWTPs typically poses an engineering problem. The flow to treat and the pollutant concentrations in the wastewater are the input data which determine the plant's size. One team of engineers is usually sufficient to perform this work [Alemany *et al.* (2004) and Adenso-Díaz *et al.* (2005)].

The main objective of the second part of the PSARU, the so-called PSARU 2002, was the definition of WWTPs for approximately 2,500 communities with fewer than 2,000 PE. In this case, the Council Directive only specifies that the level of treatment must be appropriate. This means the treatment of urban wastewater by any process and/or disposal system which, after discharge, allows the receiving waters to meet the relevant quality objectives and the relevant provisions of this and other Community Directives. This definition makes it necessary to consider aspects of (a) the small community and landscape, (b) the ecological status of the receiving media and (c) all the wastewater treatment technologies available for small communities (both high-loaded and low-loaded) [Collado (2003), Alemany *et al.* (2004) and Adenso-Díaz *et al.* (2005)]. Additionally, small communities (even in developed countries) have certain associated inconveniences, which also have to be considered in the selection of the most appropriate technology:

- Severely strained budgets for the costs of their wastewater collection and treatment facilities [EPA (1992), Nelson and Dow (1994), EPA (1999) and Loudon (2004)].
- Low level of technical expertise of many operating personnel [EPA (1992) and Loudon (2004)].
- The populace's real perception of an existing WWTP differs between an urban dweller, who in most cases is not conscious of it, and a rural dweller, who is aware of it and suffers its malfunctioning when this occurs [Alemany *et al.* (2004) and Loudon (2004)].

Inadequate budgets and poor access to equipment, supplies and repair facilities preclude proper operation and maintenance [EPA (1999)]. Also the EPA (1992), Crites and Tchobanoglous (2000), Loudon (2004) and Ho (2005) associate the failure of small-scale systems to lack of proper operation and maintenance.

Hence, the particularities of wastewater treatment in small communities can be summarized by:

(1) Complexity associated to the selection of the most appropriate technology because it is necessary to integrate technical (i.e. engineering, natural-based treatment technologies, environmental issues, etc.), economic and ecological aspects with social sensibilities (i.e. municipalities, ecological groups, etc.). This approach requires the use of qualitative and quantitative data and knowledge.

(2) Scarce availability of economic, human and technical resources to guarantee the correct functioning of these facilities.

In order to face up to the complexity and uncertainty of selecting the most appropriate wastewater treatment technology for small communities, Water Managers at the Planning Department of the Catalan Water Agency induced the development of the EDSS-treatment.

4.1.2. Wastewater treatment technologies for small communities

To address the common problems observed in small wastewater treatment plants, technologies for these facilities have to fulfil the following requirements [EPA (1992), Alexandre *et al.* (1998), EPA (1999) and Collado (2003)]:

a) Economic to construct and operate.

b) Simple to operate and maintain.

c) Low environmental impact.

A recent survey of on-site wastewater treatment technologies found at least seventy different on-site technology alternatives [Green and Ho (2004)]. However, only a few of these are used to treat the wastewater of communities with fewer than 2,000 PE. Thirteen technologies were recommended in the EDSS-treatment resulting from the PSARU 2002 project. Similar recommendations were made by the EPA (1992), Alexandre *et al.* (1998), Crites and Tchobanoglous (2000), European Community (2001) and Collado (2003) (Table 4.1).

Table 4.1. Recommended technologies to treat wastewater in small communities.

Wastewater treatment technology	EPA (1992)	Alexandre *et al.* (1998)	Crites and Tchobanoglous (2000)	European Community (2001)	PSARU (2002)	Collado (2003)
Primary treatment:						
Septic tank		X	X		X	X
Imhoff tank		X	X		X	X
Anaerobic pond			X			X
Primary settler			X		X	X
UASB Reactor						X
Secondary treatment:						
Constructed wetland	X	X	X	X	X	X
Stabilization pond	X	X	X	X	X	X
High-rate pond	X	X		X	X	X
Intermittent sand filter	X	X	X	X	X	X
Buried sand filter	X	X	X		X	X
Plant soil treatment	X		X		X	X
Trickling filter	X		X	X	X	X
Rotating biological contactor		X	X	X	X	X
Extended aeration	X	X	X	X	X	X
Sequencing batch reactor	X		X		X	X

Table 4.1 shows that common primary treatments are the septic tank and Imhoff tank. In both technologies wastewater flows through the tank at a reduced speed, allowing the sedimentation of suspended solids. These solids remain at the bottom of the tank until they are removed. Although sedimentation is the main process, flotation also occurs. The latter allows foams and floating substances to be removed. While the septic tank is recommended for communities with fewer than 300 PE, the Imhoff tank can be used from 250 to 1,000 PE [Water Environment Federation (1996), Alexandre *et al.* (1998) and Crites and Tchobanoglous (2000)].

The operation and maintenance activities of these primary treatments are focused on the removal of suspended solids accumulated at the bottom of the tank and foams accumulated at the top of the treatment unit. Whereas the suspended solids are removed every 6 months to 2 years, foams have to be taken off weekly or monthly [Water Environment Federation (1996), Alexandre *et al.* (1998) and Crites and Tchobanoglous (2000)]. If these simple activities are not carried out, problems downstream of these treatment units can appear due to pollutant overload.

According to Table 4.1 common secondary treatments are constructed wetland, stabilization pond, intermittent sand filter and extended aeration. While extended aeration is considered a high-loaded technology, the others are low-loaded techniques.

- **High-loaded technologies:**

The principle of high-loaded technologies is to operate on a reduced surface area in order to intensify the naturally-occurring phenomena of organic matter transformation and destruction [European Community (2001)]. The extended aeration process consists of mixing and stirring raw sewage with recycled activated sludge, which is bacteriologically very active. Aerobic degradation of the pollution takes place by thoroughly mixing the purifying micro-organisms and the influent to be treated. Then, "purified water" and "purifying sludge" phases are separated (Figure 4.1).

Figure 4.1. Extended aeration WWTP.
[http://www.watercorporation.com.au/graphics/bunbury2_l.jpg]

The extended aeration system operates at high sludge retention time, resulting in a condition where nitrification and endogenous respiration may occur. This situation results in a high quality treated effluent with low solids production [Water Environment Federation (1996) and Alexandre *et al.* (1998)]: 95% of the BOD_5 and 50-90% of the total nitrogen can be removed.

This technology operates at relatively low organic loads and high hydraulic retention times, so biological reactors are quite voluminous. This limits the application of this technique to small communities. Nevertheless, this technology is not recommended for fewer than 400 PE because of its high energy consumption, the skilled personal needs and regular operation and maintenance requirements [Alexandre *et al.* (1998)]. The extended aeration process involves sensors, online controllers, oxygen suppliers, pumps, etc. and operation and maintenance activities therefore have to guarantee the performance of these elements. These tasks involve simple visual controls, sensor calibrations, mechanism lubrications, etc. Most of these activities must be carried out daily.

- **Low-loaded technologies:**

Those techniques known as low-loaded involve processes which purify by means of fixed film cultures on small media (i.e. constructed wetland and intermittent sand filter) or suspended growth cultures which use solar energy to produce oxygen by photosynthesis (i.e. waste stabilization pond). Low-loaded technologies can be distinguished from high-loaded techniques by the fact that this type of facility can operate without electricity. Another feature of low-loaded techniques is that applied surface loads are very low [European Community (2001)].

Constructed wetlands are artificial wastewater treatment systems consisting of shallow (usually less than one meter deep) ponds or channels which have been planted with aquatic plants, and which rely upon natural microbial, biological, physical and chemical processes to treat wastewater. They typically have impervious clay or synthetic liners, and engineered structures to control the flow direction, liquid detention time and water level. Depending on the type of system (free surface constructed wetland, vertical subsurface constructed wetland or horizontal subsurface constructed wetland), they may or may not contain an inert porous media such as rock, gravel or sand [EPA (1999)] (Figure 4.2). Constructed wetlands are recommended for communities from 25 up to 2,000 PE [Alexandre *et al.* (1998)].

Figure 4.2. Constructed wetland WWTP.

A waste stabilisation pond system is a set of connecting basins, of varying area and depth, inside which a complex symbiosis of bacteria and algae convert the organic content of wastewater into more stable and less offensive forms. Moreover, the high hydraulic retention time allows the concentration of pathogens (bacteria, viruses and parasites) to be reduced [Alexandre *et al.* (1998)]. Lagoon systems are traditionally designed with earthen dikes lined with compacted, natural materials such as clay. However, newly constructed stabilization ponds are lined with synthetic barriers or composites of natural and synthetic barriers. The inlet structure for small lagoons is at the centre whereas large ponds employ inlet diffusers with multiple outlet ports to distribute wastewater over a larger area. Outlet structures should permit the controlling of water depth [Water Environment Federation (1996)] (Figure 4.3). Waste stabilization ponds are recommended for communities from 100 to 2,000 PE [Alexandre *et al.* (1998)].

Figure 4.3. Waste stabilization pond WWTP.

The intermittent sand filter is a treatment process based on aerobic biological filtering through a fine granular medium. Although physical and chemical processes play an important role in the removal of many particles, biological processes play the most important role in sand filters. Intermittent sand filters are typically built below grade and lined with an impermeable membrane where required. The under-drain is surrounded by a layer of graded gravel and crushed rock, with the upstream end brought to the surface and vented. Pea gravel is then placed on top of the graded gravel and then sand is laid over the top of the pea gravel. Wastewater is successively distributed over several infiltration units. The distribution area for the water is maintained in the open air and is visible [Alexandre *et al.* (1998) and European Community (2001)] (Figure 4.4). Intermittent sand filters are recommended for communities from 100 up to 2,000 PE [Alexandre *et al.* (1998)].

Figure 4.4. Intermittent sand filters WWTP.

Low-loaded systems have only few mechanical parts, on-line controllers, sensors, etc. Hence, operation and maintenance activities are focused on maintaining the water level, guaranteeing water distribution, avoiding matrix clogging, assuring plant health, etc. For instance, the principal maintenance activity in constructed wetlands is to cut the macrophytes once a year and clean the wastewater distribution system. In waste stabilization ponds the principal operation and maintenance activity consists in removing sludge accumulated at the bottom of lagoons every 5-10 years, and in intermittent sand filters it consists in removing the sludge accumulated over the filter between two feeding periods and cleaning the wastewater distribution system.

Since constructed wetland is the alternative most recommended by EDSS-treatment (up to 400 of the 1,400 WWTPs proposed by the EDSS-treatment are based on constructed wetland technology), we decided to develop an EDSS-maintenance prototype for this technique, specifically for the HSCW configuration because is the most common constructed wetland design [Vymazal (2005)].

4.1.3. Horizontal subsurface constructed wetlands

Despite the fact that the term wetland describes a diverse spectrum of ecological systems (i.e. marshes, bogs, swamps, wet meadows, tidal wetlands, floodplains, ribbon (riparian) wetlands along stream channels), common features characterize these ecosystems [EPA (1999)]. From these general characteristics a wetland can be defined as an area that is frequently flooded or saturated at surface or ground level, with a duration and depth sufficient to support the predominance of plant species adapted to growth in saturated soil conditions.

Natural wetlands have been used as convenient wastewater discharge sites for as long as sewage has been collected. When monitoring of some existing discharge sites was initiated, an awareness of the water quality depuration potential of wetlands began to emerge [Kadlec *et al.* (2000)]. This potentiality was the starting point of constructed wetland technology.

Constructed wetlands are wetlands which are purposely constructed by humans in a non-wetland area to reproduce the natural sanitation processes that occur in a natural wetland. There are two types of constructed wetlands; they share many characteristics but are distinguished from one other by the location of the hydraulic grade line [EPA (1999)]:

- **Surface flow constructed wetland** consists of a shallow basin, soil or other medium to support the plant roots and a water control structure that maintains a shallow depth of water. The water surface is above the substrate (Figure 4.5) [Core Group (2000)].

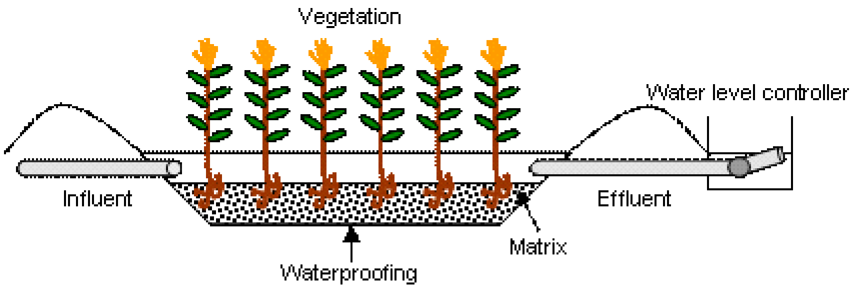

Figure 4.5. Surface flow constructed wetland diagram.

- **Subsurface flow constructed wetland** consists of a sealed basin with porous substrate of rock or gravel. The water level is designed to remain below the top of the substrate. The flow path can be vertical (Figure 4.6.A) or horizontal (Figure 4.6.B) [Core Group (2000)].

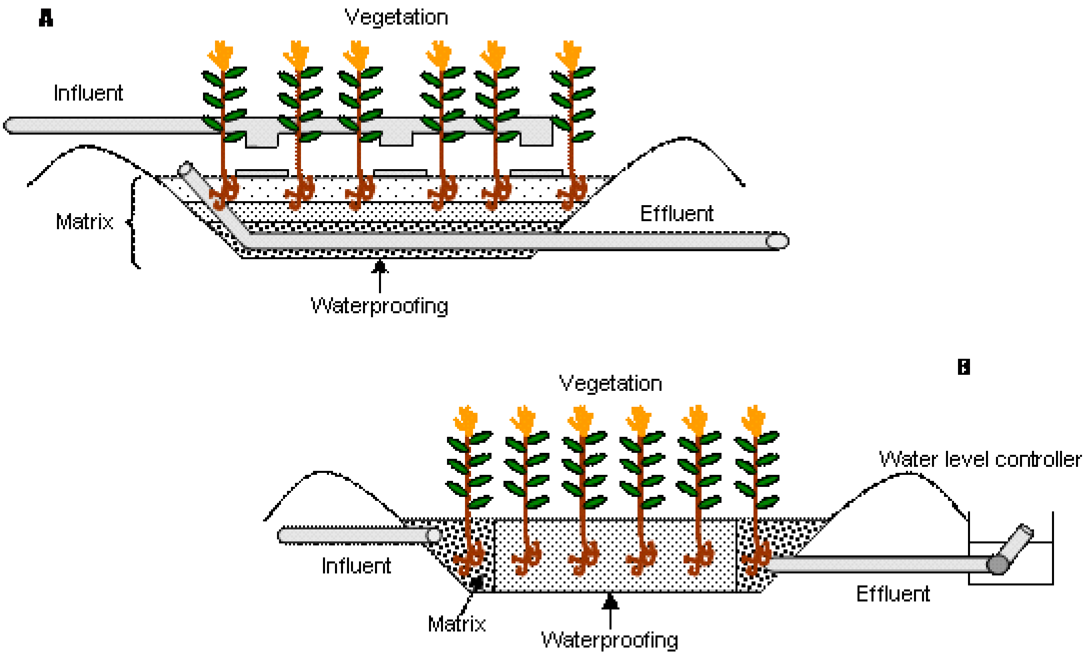

Figure 4.6. Subsurface flow constructed wetland diagram:
A) vertical flow and B) horizontal flow.

The structure object of the investigation into developing the EDSS-maintenance prototype is that of the subsurface horizontal flow (Figure 4.6.B), it being the most common according to Vymazal (2005). In this structure, wastewater flows horizontally through a gravel bed contained in a waterproofed basin. Wastewater enters through one end of the basin via the distribution system and flows slowly through the porous medium until it reaches the other end. The water flow is produced by gravity due to a slope of approximately 1% from the base of the basin. At the opposite end of the wastewater inlet there is a collection system for treated water, usually a corrugated, perforated tube connected to a mechanism which regulates the water level in the basin [Cooper (1996), Kadlec and Knight (1996), Taylor (1998) and Kadlec *et al.* (2000)]. As can be seen in Figure 4.6.B, the macrophytes which also take part in the purifying process take root in the matrix or substrate through which the wastewater flows. In point 4.1.3.1 HSCW components below, each of the HSCW components are described in more detail.

4.1.3.1. HSCW components

- **Vegetation:**

Vegetation is one of the main components of the HSCW. Its contribution to the treatment of wastewater may be summarised in the following points:

- It stabilises the substrate and regulates the flow [EPA (1999), Lara and Salgot (1999), Kadlec *et al.* (2000), Vymazal (2002) and García *et al.* (2003)].
- It incorporates organic material, nutrients and trace elements [EPA (1999), Lara and Salgot (1999), Kadlec *et al.* (2000) and García *et al.* (2003)].
- It transfers gases between the atmosphere and the matrix [EPA (1999), Lara and Salgot (1999), Kadlec *et al.* (2000) and García *et al.* (2003)].
- The stem and the root system act as a support for the fixation of microorganisms [EPA (1999), Lara and Salgot (1999), Kadlec *et al.* (2000), Vymazal (2002) and García *et al.* (2003)] and also intervene in pollutant filtration processes [Vymazal (2002)].
- Those parts of the plant which are exposed to the air insulate the system from low temperatures [EPA (1999), Kadlec *et al.* (2000) and García *et al.* (2003)].
- The movement of the plants in the wind keeps the substrate surface open [Brix (2003)].
- The growth of the roots in the filter medium helps the decomposition of the organic material and avoids clogging the matrix [Brix (2003)].

Given that vegetation plays an important role in HSCWs, special attention must be paid to (1) plant selection, (2) careful selection of the plantation period, (3) preparing cells for plantation, (4) plantation itself and (5) establishing and managing the planted macrophytes.

1) Plant selection

The macrophytes selected for treating the wastewater in a HSCW must fulfil the following requirements [EPA (1999) and Seabloom and Hanson (2003)]:

- They must be active colonisers with an extensive root system.
- They must provide a uniform vegetation cover over the HSCW.
- They must be native to the area, as if they are not, problems of competition and invasion may occur.

According to the EPA (1988), Lara and Salgot (1999) and the Core Group (2000), the macrophytes which fulfil these requirements are those of the genus: *Scarp's*, *Eleocharis*, *Cyperus*, *Juncus*, *Phragmites* and *Typha*. Of the species mentioned above, *Phragmites australis* is the most common in European constructed wetlands [Cooper *et al.* (1996), Lara and Salgot (1999), Kadlec *et al.* (2000) and Brix (2003)], due to its tolerance of different climatic conditions and its rapid growth [Cooper *et al.* (1996)].

At the plant selection stage, the plants' origin must also be considered [Core Group (2000)]:

- **Seeds:** Sowing seeds is the simplest, but not the most efficient method, as the majority of seeds do not develop properly [Cooper *et al.* (1996), EPA (1999), Core Group (2000) and Seabloom and

Hanson (2003)]. According to Brix (2003) the seed germination process lasts from 7 to 9 days and the percentage of seeds germinated varies from 30 to 100% depending on:

- The temperature [Cooper *et al.* (1996), Core Group (2000) and Brix (2003)].
- The hours of daylight [Brix (2003)].
- The water level in the cells [Cooper *et al.* (1996), Lara and Salgot (1999) and Core Group (2000)].
- The availability of nutrients [Cooper *et al.* (1996) and Core Group (2000)].

— **Plants:** Plantation using whole plants is the method which facilitates the fastest total coverage of the HSCW surface [Vymazal (2002)]. However, the following requirements must be observed [Hoag (1998) and Taylor *et al.* (1998)]:

- That plants are free of disease and/or fungi.
- That the roots of the plants are kept moist up to the moment of plantation.
- An adequate water level is maintained after planting.

In small treatment systems the vegetation may be transplanted directly to nearby zones [Crites and Tchobanoglous (2000)].

— **Rhizomes:** Plantation with rhizomes is not recommended due to the high mortality rate (survival figures do not exceed 50%) [Brix (2003)] and because plant cover occurs very slowly [Cooper *et al.* (1996) and Vymazal (2002)]. Furthermore, this system of plantation involves a high risk of transplanting weeds [Vymazal (2002)].

2) Plantation period

In the bibliography consulted certain divergences are observed when defining the optimum plantation period. This variability is due to both the geographical location of the HSCW and the origin of the plants:

— The European Community (1990), Europe, states that plantation is possible from spring to autumn, although it does not recommend planting once summer has begun, especially when dealing with plantations using seeds.

— Cooper *et al.* (1996), Europe, state that transplantations may be carried out all year round, although they recommend the May to August period. Plantations carried out during winter may be affected by (1) frosts, (2) rabbit plagues and (3) possible diseases, such as chlorosis.

— Geller (1997), Europe, considers that the best time for plantation is at the end of spring, from May to June.

— Campbell and Ogden (1999), USA, state that plantation must take place during the spring, and do not recommend planting at the end of summer or the beginning of autumn, as during this period the plants do not have enough time to establish themselves before the frosts.

— The EPA (1999), USA, state that in temperate climates the optimum plantation period starts from the end of the plant latency period to the first third of summer.

— The Core Group (2000), USA, recommends planting during the period from the end of summer to the beginning of the following summer. Despite this general proposal, they recommend that plantation using rhizomes be carried out during the autumn, and that plantation using whole plants be carried out during the spring.

- Kadlec *et al.* (2000), Europe, state that the best period for plantation is at the beginning of the growing season which usually coincides with spring and the beginning of summer.
- The Georgia Department of Natural Resources (2002), USA, recommend planting from the beginning of April to the middle of July, and recommend doing this before applying wastewater to the HSCW (they recommend that water supplied during the plantation period should not be wastewater).
- Vymazal (2002), Europe, recommends planting *Phragmites australis* seeds from the end of April to the end of September.

For the Catalan HSCW, we recommend planting from the beginning of spring to the beginning of summer (from March to July).

3) Preparing the basins for plantation

Tousignant *et al.* (1999) and the Core Group (2000) recommend carrying out the following steps before beginning plantation:

- Rake the surface of the HSCW once the gravel has been deposited and compacted in order to break the compact surface of the topsoil. A minimum of 30 cm of non-compacted soil is recommended.
- Lightly flood the constructed wetland in order to relocate and level the raked soil.
- Drain the HSCW in order to ensure that the substrate is moist, but not flooded during plantation.

4) Plantation

The plantation of macrophytes is carried out either manually or automatically depending on the area to be planted and/or the plantation system chosen:

- **Seed plantation:** Kadlec *et al.* (2000) state that the plantation of seeds may be carried out manually in small systems and mechanically – by means of mechanical elements which help to turn over the first few centimetres of substrate to plant the seeds – in large systems.
- **Planting whole plants:** The Core Group (2000) states that the plantation of whole plants is normally performed manually, ensuring that the roots and/or rhizomes are at the same level as the water level planned for system usage. The growth of the roots or rhizomes must be downwards, and in order to promote this penetration the following measures are proposed (1) reducing the water level or (2) dividing the constructed wetland into different cells and establishing flooding-draining cycles. Molle [Oral communication (2004)] also recommends that the water level should be accessible for the plant roots during plantation, and that the level should be lowered to promote root growth.
- **The plantation of rhizomes:** Recommendations for carrying out rhizome plantation were not found in the bibliography consulted.

Whatever the plantation system chosen, Tousignant *et al.* (1999) and the Georgia Department of Natural Resources (2002) recommend that plantation be carried out before the treatment system begins to operate using wastewater, and they suggest that there should be a period of 4 to 6 weeks between plantation and the application of wastewater.

Tousignant *et al.* (1999) propose the following actions during the plantation of *Phragmites australis* in order to avoid later weed growth on the constructed wetland surface:

- Buying certified seeds or plants free from weeds.
- Programming activities in order to minimise the germination of weeds.
- Raking or breaking up the ground before planting.
- Planting a high density of *Phragmites australis* (competition).

In this respect, planting a high density of *Phragmites australis* would imply the plantation of more than 4 plants per m^2, as although the number of plants recommended per surface unit varies according to the bibliography consulted [Kadlec and Knight (1996), EPA (1999), Lara and Salgot (1999), Crites and Tchobanoglous (2000), Kadlec *et al.* (2000), Vymazal (2002) and Molle (Oral communication 2004)] this plantation density is recommended for the Catalan HSCWs.

5) Establishment of the vegetation

Whatever the chosen planting method, steps must be followed in order to guarantee the establishment of the vegetation.

- Controlling the water level to prevent the constructed wetland drying out (a situation which inhibits the growth of the plants and promotes the proliferation of weeds), or preventing flooding (conditions which may provoke the exhaustion of oxygen to the root area, and as a consequence growth will be slower, and even provoke the death of the plants) [Kadlec *et al.* (2000) and Brix (2003)].
- Checking for the growth of invading plant species and if found, removing them [Brix (2003)].

In order to verify the correct growth of the planted vegetation Kadlec and Knight (1996) and Kadlec *et al.* (2000) recommend periodical visits to ensure the correct establishment of the vegetation so as to (1) verify the viability of the system of plantation chosen and (2) evaluate the growth of the plants through estimation of the percentage of average coverage and height. In this respect Kadlec and Knight (1996) recommend inspecting the plant cover of the HSCW some 60 days after plantation. The visit will be considered satisfactory if:

- There is a 1 m separation between the plants.
- The survival percentage is above 80%.
- There are no areas where plant survival is below 50%.

In order to estimate the plant percentage cover of the HSCW, Kadlec and Knight (1996) recommend making transects. The transects consist of a number of itineraries laid out in specific directions from a pre-fixed area in order to note the changes in the vegetation [Conesa (1997)]. There are different types of transects depending on the method used. For the study of *Phragmites australis* in the constructed wetland the following are recommended:

- <u>Strip length method:</u> This consists in noting the number of plants which appear on a given strip of land (the transect), generally 1 m wide.
- <u>Linear method:</u> The plants found under a linear itinerary, defined by a taut cord are noted. The plants are noted at specific distances of 5 or 10 cm.

6) Maintenance of the vegetation

Once the vegetation has been established, normally a year after plantation [Molle (Oral communication 2004)], cutting of the plant cover is recommended. This action helps to (1) maintain the hydraulic capacity of the system [Crites and Tchobanoglous (2000)] and (2) promote the active growth of the plants [Campbell and Ogden (1999) and Crites and Tchobanoglous (2000)]. According to Bécares (2004), the cutting of the vegetation promotes the supply of oxygen to the subsoil, minimising the accumulation and degradation of the material and promoting the elimination of nutrients, whilst improving water circulation and the control of mosquitoes.

The period recommended for cutting varies according to the literature consulted:

- Campbell and Ogden (1999) consider the best time for cutting the vegetation to be at the peak of the growing season, at the moment when nitrogen elimination is greatest. However, if what is required is a HSCW with an acceptable appearance, cutting is recommended in autumn.
- The EPA (1999) recommend cutting just before the end of the growing period.
- The California Stormwater Quality Association (2003) recommends cutting the vegetation during the summer.
- Bécares (2004) recommends that in the Mediterranean, vegetation should be cut from March to April, months when the risk of frosts is low and solar radiation is moderate.
- Molle [Oral communication (2004)] recommends cutting in the autumn, the period when *Phragmites australis* is dry. This promotes aeration, reduces the accumulation of vegetable debris on the constructed wetland surface and thus avoids clogging the matrix.

The PSARU-2002 recommends that the plants should be cut when they are dry, leaving some 30 cm of stem in order to promote the entrance of oxygen into the medium, while Molle [Oral communication (2004)] recommends cutting the plants to a length of approximately 5 – 10 cm from the surface of the substrate.

The EPA (1999) states that plant-cutting tasks can be reduced simply by direct burning. Some experiences in Spain confirm the use of this action which is recommended as (1) the process is much faster and more economical and (2) the ashes need not be removed from the constructed wetland surface, as for the moment, no risk of matrix obstruction has been observed.

Although cutting the vegetation has certain advantages, some authors such as Vymazal (2002) consider this measure to be unnecessary, as once uncut plants have died, they provide insulation for the constructed wetland surface during the coldest months.

- **Matrix:**

The matrix or substrate is one of the most important components of the HSCW as it intervenes in the development of the system in a variety of ways:

- It allows the vegetation to take root [EPA (1999) and Vymazal (2002)].
- It contributes to the homogeneous distribution of the water flow [EPA (1999) and Vymazal (2002)].
- It supplies surfaces for the growth of microorganisms [EPA (1999)].
- It acts as a filter medium [EPA (1999) and Vymazal (2002)].

The type and measurement of substrate are factors which may influence the correct development of the functions associated with the gravel matrix. As such, as Cooper *et al.* (1996) recommend, they must be considered when choosing the HSCW substrate.

1) Types of substrate

The gravel which forms the matrix of a HSCW must be:

- Resistant to compression and/or breakage [EPA (1999)].
- Resistant to corrosion or dissolving by the wastewater [Hyngstrom *et al.* (2002)]. Sanford *et al.* (1995) and the Georgia Department of Natural Resources (2002) do not recommend the use of limestone due to the high level of breakage and dissolving which occur.
- Clean and free of particles that could reduce the hydraulic capacity of the matrix [Cooper *et al.* (1996), Kadlec and Knight (1996), EPA (1999), Mashauri *et al.* (2000), Georgia Department of Natural Resources (2002) and Seabloom and Hanson (2003)].
- Free from seeds which, on germinating, may promote the growth of weeds, trees and/or bushes [Tousignant *et al.* (1999)].

The substrate recommended for HSCWs in Catalonia must fulfil the characteristic specified in the previous points: it should be formed by previously washed gravel which is resistant to compression and corrosion, insoluble in wastewater, and free from plant seeds.

2) Substrate measurements

Sanford *et al.* (1995), the EPA (1999) and Economopoulou and Tsihrintzis (2003) recommend the use of medium-coarse grade gravel, and do not recommend the use of soil or earth, as these are highly susceptible to clogging. According to Lara and Salgot (1999) hydraulic conductivity (ks) increases with the diameter of the substrate particles and its porosity percentage (Table 4.2), which means that using medium-coarse grade gravel (1) the capacity of the matrix to transmit the flow of wastewater is increased, and (2) obstruction is avoided.

Table 4.2. HSCW substrate characteristics
[Source: Lara and Salgot (1999)]

Substrate type	Effective measurement D_{10} (mm)	Porosity n (%)	Hydraulic conductivity ks ($m^3/m^2/d$)
Coarse sand	2	28-32	100-1,000
Stony sand	8	30-35	500-5,000
Fine gravel	16	35-38	1,000-10,000
Medium gravel	32	36-40	10,000-50,000
Coarse gravel	128	38-45	50,000-250,000

In order to facilitate the distribution and collection of wastewater, Sanford *et al.* (1995), Cooper *et al.* (1996), the EPA (1999), Crites and Tchobanoglous (2000), the Georgia Department of Natural Resources (2002) and Seabloom and Hanson (2003) recommend distributing the gravel so that the gravel at the wastewater inlet and outlet zones is larger in diameter than that in the central area of the system (Figure 4.6.B). The EPA (1999) and Seabloom and Hanson (2003) recommend coarse gravel of 40-80 mm in the inlet and outlet zones. With regard to the diameter of the gravel in the central part of the HSCW, the size differs depending on the author:

- 5-10 mm [Cooper *et al.* (1996)]
- 12-25 mm [Campbell and Ogden (1999)]

- 20 mm [Koottatep *et al.* (1999)]
- 3-32 mm [Crites and Tchobanoglous (2000)]
- 21-24 mm [Mashauri *et al.* (2000)]
- 20-30 mm [Seabloom and Hanson (2003)]

For the Catalan HSCW, a strip of 1.5 m of medium grade gravel is recommended (D_{10} = 32 mm and ks = 10,000-50,000 $m^3/m^2/d$) at the wastewater inlet and outlet zones, and fine grade gravel in the central area (D_{10} = 16 mm and ks = 1,000-10,000 $m^3/m^2/d$).

- **Water control:**

One important characteristic of the HSCW is that the water flows under the surface of the matrix, continually and uniformly through the entire cell. In routine situations, maintaining a water level some 5 to 10 cm under the surface of the matrix is recommended [Crites and Tchobanoglous (2000), Hygnstrom *et al.* (2002) and Aguirre (2004)]. However, there are specific situations in which the water level must be varied in order to maintain the system in proper conditions or for undertaking maintenance tasks. Some of the situations where reduction of the water level is recommended are:

(1) The initial operations period of the system: Once vegetation has been established, Campbell and Ogden (1999) and Crites and Tchobanoglous (2000) recommend gradually decreasing the water level in order to promote the deeper growth of the roots.

(2) In the summer: According to Kadlec and Knight (1996), during the months when temperatures are higher the productivity of the plants is at its maximum. With the reduction in the water level the diffusion of oxygen in the root zone is improved.

(3) Before cutting in order to provide greater soil consistency and facilitate the work of both operators and/or machinery.

However, increasing the water level is recommended in order to combat the growth of invading plants. Tousignant *et al.* (1999) and the Core Group (2000) state that this increase may be from 2 to 5 cm, Green and Upton (1995) state that in these situations the water level may be increased by up to 20 cm, and Brix (2003) proposes making an increase of up to 30 cm. In any event, it is important that the water level does not cover the vegetation and that flooding is not prolonged (from a week to 2 months, depending on whether the flooding is carried out with wastewater or clean water).

- **Water distribution systems:**

The most common HSCW wastewater distribution systems are:

- Perforated tubes approximately 120 mm in diameter which are laid across the entire breadth of the cell (Figure 4.7). The perforated distribution tubes minimise the possibility of short circuits and the blocking of the media, and maximise the distribution of the flow throughout the system [EPA (1999) and Tousignant *et al.* (1999)]. The EPA (1999) states that the distance between the perforations in the tube must be approximately equal to 10% of the cell width, that is, if the width is 20 m, the distance between the perforations must be 2 m.

Figure 4.7. Wastewater distribution system through a perorated tube.

– Constructed channels which run across the widths of the cell. These channels may be (1) covered constructed channels, which provide the advantage of the wastewater remaining out of contact with the atmosphere, and the cell filtration system is made through "V" shaped openings [Cooper *et al.* (1996)], at a distance of 2-5 m apart, or (2) open constructed channels. The water enters the cells when the channel is full and flows onto the surface (Figure 4.8).

Figure 4.8. An open channel wastewater distribution system.

- **Water collection systems:**

The most common water collection system is that of a perforated, buried tube (Figure 4.9). These tubes are some 200 mm in diameter and are buried in the outlet zone in order to facilitate the collection of water and ensure complete drainage when necessary. They are generally connected to the water level regulatory system.

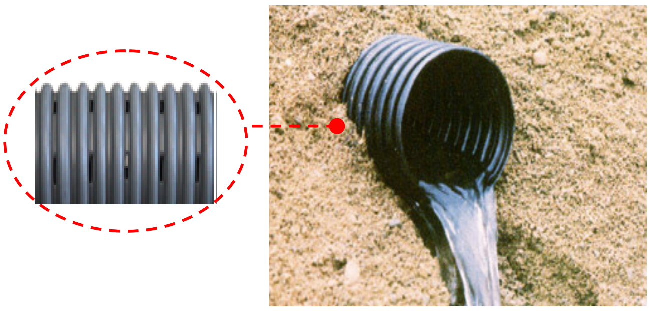

Figure 4.9. Wastewater collection system using a perforated tube.

- **Water level control systems:**

In the majority of HSCW, there is a device at the outlet to regulate the water level [Cooper *et al.* (1996), EPA (1999), Lara and Salgot (1999) and Tousignant *et al.* (1999)]. This device generally consists of a rigid tube in the shape of an elbow (Figure 4.10.A) or a flexible tube which is secured with a chain (Figure 4.10.B).

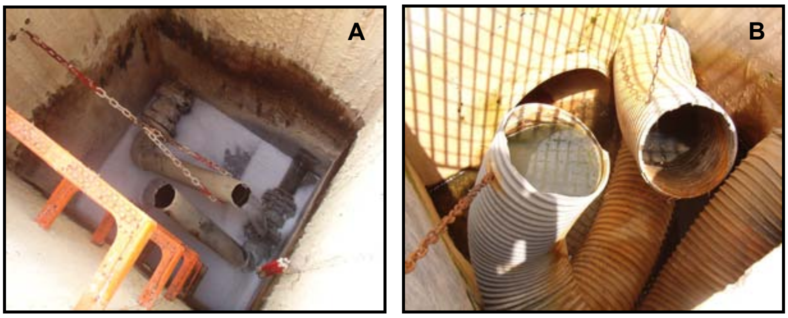

Figure 4.10. Water level control device: A) rigid tube and B) flexible tube.

When the device is in a vertical position, the water level in the cell is at its maximum height. As the water level drops so the device inclines (Figure 4.11).

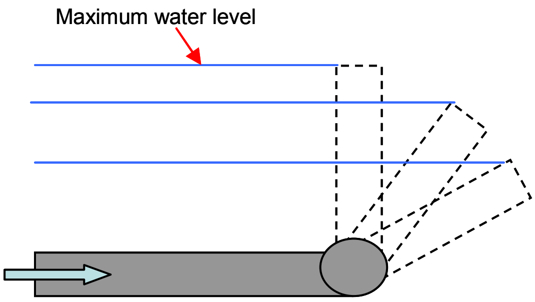

Figure 4.11. Diagram to show how the water level regulatory device functions.

- **Waterproofing:**

HSCWs require a waterproof barrier which impedes the wastewater from contaminating the subsoil or aquifers [Campbell and Ogden (1999) and Kadlec *et al.* (2000)], and ensures that underground water cannot enter the HSCW [Terraforms (2002)].

1) Types of waterproof layer

Taylor *et al.* (1998), Campbell and Ogden (1999), the EPA (1999), Kadlec *et al.* (2000), Terraforms (2002), Vymazal (2002) and Seabloom and Hanson (2003) state that in order to prevent contamination, barrier materials are essential, such as PVC, low and high density polyethylene and also compact clay or other materials which may be found in the HSCW location area, and which once compacted may become almost impermeable. Lara and Salgot (1999) and Hygnstrom *et al.* (2002) add bentonite or asphalt layers to this list. Píriz (2004) recommends waterproofing with layers of PVC or cork, as these synthetic layers offer greater flexibility even though they are more expensive.

2) Characteristics of the waterproof layer

The membrane must be resistant and not puncture with the weight of the gravel or the growth of the roots [Tousignant *et al.* (1999) and Kadlec *et al.* (2000)]. The membrane must also be resistant to:

- Ultra Violet (UV) radiation. Campbell and Ogden (1999) warn that although layers of PVC are the most resistant to perforation, they are also highly sensitive to UV radiation. Therefore, covering this type of waterproof layer with a UV radiation-protective membrane is recommended [Taylor *et al.* (1998), Campbell and Ogden (1999) and Vymazal (2002)]
- Inclement weather. In this respect Píriz (2004) recommends that the climatic conditions of the area where the constructed wetland is located should be taken into consideration in order to avoid problems with deformation of the waterproof layer caused by temperature.

Where synthetic materials are used, it is recommended that the waterproof layer has a thickness between 5-10 mm [Kadlec *et al.* (2000)]. Where the waterproof layer is made from compacted soil a minimum thickness of 300 mm is recommended [EPA (1999), Tousignant *et al.* (1999) and Seabloom and Hanson (2003)].

3) Positioning the waterproof membrane

Care must be taken during the positioning of the waterproof membrane as it may become perforated due to the gravel substrate. In order to avoid this:

- Lara and Salgot (1999) recommend insulating the bottom of the constructed wetland before disposition of the membrane.
- Píriz (2004) recommends that once the waterproof membrane has been posted that it is protected with a geotextile membrane beforehand so that the gravel is not left on the surface.

The waterproof membrane must cover the entire surface area of the cell and must be secured to the upper part of the dikes (Figure 4.12) [Píriz (2004)].

Figure 4.12. Photograph showing the waterproof membrane of an HSCW secured to the upper part of a dike.

- **Dikes:**

Dikes are formed by the accumulation of compacted soil, normally the soil which has been extracted to make the HSCW cells [Tousignant *et al.* (1999)], and their purpose is to (1) limit the surface area occupied by each cell, and (2) avoid run-off water reaching the cells [Terraforms (2002)]. The main characteristics of these structures are:

- The external slope of the dikes: 3:1 [Campbell and Ogden (1999), EPA (1999), Tousignant *et al.* (1999) and Seabloom and Hanson (2003)] (Figure 4.13). However on some occasions the slope is at a 0% incline as the cells are excavated in the soil [EPA (1999)].

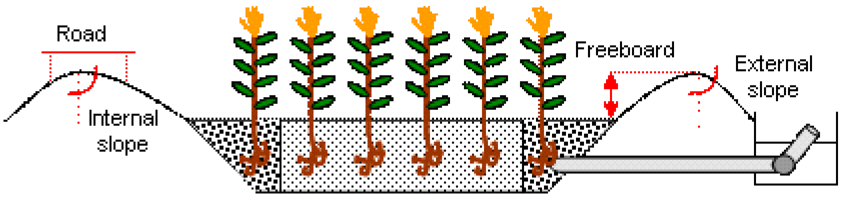

Figure 4.13. Parts of an HSCW dike.

- The inner slope of the dikes: 2:1 [EPA (1999) and Tousignant *et al.* (1999)] (Figure 4.13).
- The dike crown (road): 60 cm wide in order to permit employee access [Campbell and Ogden (1999)] or 2-3 m wide to facilitate maintenance tasks [EPA (1999) and Tousignant *et al.* (1999)] (Figure 4.13).
- Safety margin (freeboard): 0.6 cm - 1 m [EPA (1999)] (Figure 4.13).
- In some constructed wetlands there is a protection barrier consisting of a concrete pipe, which prevents run-off water entering (Figure 4.14).

Figure 4.14. HSCW with land-based cell with a concrete pipe at the upper part of the dike.

- Covering the external part of the dikes with vegetation [Campbell and Ogden (1999), Tousignant *et al.* (1999) and Core Group (2000)] or coarse gravel [EPA (1999) and Core Group (2000)].

4.1.3.2. HSCW depuration processes

HSCW depuration procedures are complex and involve physical, chemical and biological processes [EPA (1999), Crites and Tchobanoglous (2000) and Aguirre (2004)] including oxidation and the reduction of bacteria, filtration, chemical precipitation and adsorption. These processes permit degrees of contaminant elimination which range from 50 to 80% [Collado (1991), EPA (1992), Crites and Tchobanoglous (2000), Kadlec *et al.* (2000) and Terraforms (2002)].

- **Suspended solids**

The majority of the suspended solids are deposited in the first third of the HSCW cells. The process involved is called granular medium filtration [Metcalf and Eddy (1991)] and takes place mainly due to low water speed and high particle adhesion. The roots and rhizomes of the plants also contribute to this filtration process. It must be taken into account that the organic suspended solids, once retained in the HSCW, begin to break down, and are therefore added to the organic load transported by the influent [EPA (1999) and Aguirre (2004)]. However, when the water carries a high concentration of solids in suspension the inlet zone may become clogged, causing emersion of the flow [EPA (1999), Crites and Tchobanoglous (2000) and Kadlec *et al.* (2000)].

- **Organic matter**

In HSCWs, organic matter is transformed by means of biological mechanisms which take place mainly in anaerobic conditions [EPA (1999) and Crites and Tchobanoglous (2000)]. Organic matter is also broken down through the action of facultative bacteria which adhere to the buried parts of the plants (roots and rhizomes) and the surface of the gravel [Kadlec *et al.* (2000)]. The oxygen necessary for this decomposition is obtained directly from the atmosphere through diffusion or through the roots of the macrophytes. It is generally agreed that transport of oxygen through the roots is insufficient to guarantee facultative decomposition throughout the entirety of the matrix [e.g. EPA (1999) and Whitney *et al.* (2003)]. Other than by biological processes, part of the particulated organic matter may be eliminated by the same mechanisms as the suspended solids [EPA (1999)].

- **Nitrogen**

The elimination of nitrogen through the processes of nitrification and de-nitrification is deficient in HSCWs due to the fact that nitrification requires aerobic zones which are seldom found in these types of systems [EPA (1999), Vymazal (1999, a), Crites and Tchobanoglous (2000), Kadlec *et al.* (2000) and Vymazal (2002)]. Although nitrogen may also be absorbed through the plants' absorption processes, this is not significant compared to the loads applied when treating municipal wastewater [EPA (1999), Vymazal (1999, b), Crites and Tchobanoglous (2000), Kadlec *et al.* (2000), Otte (2003) and García (2004)]: in the case of *Phragmites australis* absorption is below 5% [Vymazal (1999, a)]. A small amount of nitrogen may be adsorbed by the matrix.

- **Phosphorous**

The elimination of phosphorous is relatively low as (1) the substrates used normally contain a low concentration of elements which serve as bonds in the elimination of phosphorous, such as iron, aluminium or calcium [Vymazal (1999, b), Kadlec *et al.* (2000) and Vymazal (2002)] and (2) the gravel used has low specific surface area. The planted macrophytes may also absorb part of the phosphorous.

- **Others**

Heavy metals are eliminated through similar processes to those which eliminate phosphorous, such as adsorption, chemical precipitation or plant assimilation [Crites and Tchobanoglous (2000)].

Pathogenic bacteria and viruses are eliminated through the processes of adsorption, sedimentation, predation and death due to exposure to unfavourable temperatures [Crites and Tchobanoglous (2000)].

4.1.3.3. HSCW advantages and disadvantages

HSCWs are a cost-effective and technically feasible approach for wastewater treatment for several reasons:

- They can be less expensive to build than other treatment options [Alexandre *et al.* (1998), Core Group (2000) and Kadlec *et al.* (2000)].
- Operation and maintenance expenses are low compared to high-loaded technical systems [EPA (1992), Alexandre *et al.* (1998), Core Group (2000), Kadlec *et al.* (2000) and European Community (2001)].
- Operation and maintenance require only periodic, rather than continuous, on-site labour [Core Group (2000) and Kadlec *et al.* (2000)].

- No highly-qualified personnel are needed for maintenance [EPA (1992) and European Community (2001)].
- They are able to tolerate flow fluctuations [Core Group (2000), Kadlec *et al.* (2000) and European Community (2001)].
- They are able to treat wastewaters with low organic load [Kadlec *et al.* (2000)].
- They facilitate water reuse and recycling [Core Group (2000) and Kadlec *et al.* (2000)].
- They provide habitat for many wetland organisms [Core Group (2000) and Kadlec *et al.* (2000)].
- They can be built to fit harmoniously into the landscape [Core Group (2000) and Kadlec *et al.* (2000)].
- They provide numerous benefits in addition to water quality improvement, such as wildlife habitat and the aesthetic enhancement of open spaces [EPA (1992), Core Group (2000) and Kadlec *et al.* (2000)].
- They are an environmentally sensitive approach viewed favourably by the general public [Core Group (2000) and Kadlec *et al.* (2000)].

However, there are also several limitations associated with the use of HSCWs:

- They generally require larger land areas than high-loaded wastewater treatment systems (wetland treatment may be economical in relation to other options only where land is available and affordable) [Core Group (2000) and European Community (2001)].
- Performance may be less consistent than in high-loaded treatment. HSCW treatment efficiencies may vary seasonally in response to changing environmental conditions, including rainfall and drought. While the average performance over the year may be acceptable, wetland treatment cannot be relied upon if effluent quality must meet stringent discharge standards at all times [Core Group (2000)].
- The biological components are sensitive to toxic chemicals, such as ammonia and pesticides [Core Group (2000)].
- Flushes of pollutants or surges in water flow may temporarily reduce treatment effectiveness [Core Group (2000)].
- There is as yet no consensus on the optimal design of wetland systems nor is there much information on their long-term performance [EPA (1992), EPA (1993) and Core Group (2000)].

4.1.4. Requirements for development of the EDSS-maintenance prototype

Once domain characterization was completed, the environmental problem analysis was focused on the identification and definition of the problem, in order to finally identify what is required to achieve an optimal solution.

The physical construction of HSCWs requires the same equipment and procedures as for other small decentralized wastewater treatment systems. However, there are aspects which are unique and require special attention, namely establishing the emergent vegetation and providing the devices necessary to ensure uniform flow through the wetlands [EPA (1999)].

Obtaining a dense, vigorous plant cover involves (1) selecting the plants, (2) planning the planting period, (3) plantation itself, (4) establishing the vegetation and finally (5) maintaining the vegetable cover. In each of these cases a series of aspects must be evaluated:

- In the selection of plants, the characteristics of the area where the HSCW is located must be taken into account in order to choose an indigenous macrophyte with an extensive root system which will provide a uniform vegetation cover in the quickest time possible.
- The plantation period must be planned to take into account the climatology of the area so as to avoid planting above all in periods when there are low temperatures.
- In the plantation itself the most appropriate planting method must be chosen with respect to the macrophyte (seed, whole plant or rhizome) and the surface to be planted.
- An essential aspect in establishing the vegetation is regulation of the water level in order to promote the growth of the macrophyte planted, and avoid the proliferation of weeds. This variation in the water level can only take place if the HSCW has a water level control mechanism.
- Maintenance of the plant cover focuses on avoiding the growth of weeds, removing this type of emerging vegetation and plant debris that has accumulated on the surface of the HSCW, as well as cutting the planted macrophytes. Annual cutting is recommended, however:
    - The period when this task is to be carried out must be chosen according to the climate of the area.
    - The cutting system (manual or mechanised) must be chosen according to the characteristics of the cells (size, access to the interior of the cells, capacity to lower the water level in the cells, etc.).
    - The management of debris left after cutting will vary according to the possibilities of burning the debris, the existence of compostage facilities, etc.

In order to ensure the correct distribution of wastewater through the cells, correct selection of (1) the matrix, (2) the wastewater distribution system and (3) the treated water collection system is essential. The choice of these three elements is based mainly on the characteristics of the wastewater being treated (quantity and quality). Although these are the main elements for guaranteeing correct water distribution, factors such as dikes or waterproofing, or the presence of mechanisms such as a water level controller, recirculation, by-pass, etc. may play an important role in water distribution. The former, dikes and waterproofing, act as structural elements for the contention of wastewater in the interior of the treatment units, and avoid water entering from other sources (i.e. rain run-off water or aquifers). The remaining mechanisms, recirculation, by-pass etc. provide the treatment plant with operational flexibility, and so improve the distribution of wastewater.

As mentioned previously, constructed wetland is the most highly recommended technology for the EDSS-treatment used in the PSARU 2002 project. This treatment programme covers a group of programmes which have as their overall objective the improvement of the ecological state of water courses and receiving media in Catalonia. In these terms it is not enough to choose the most appropriate treatment system for each community, as a technical follow-up procedure must be carried out to ensure the correct operation of the WWTPs to be implemented as treatment solutions.

The technical follow-up procedure for an HSCW is based on a series of measures and actions focused on (1) guaranteeing the establishment of a dense and vigorous plant cover, and (2) ensuring a homogenous distribution of wastewater through the gravel bed. These objectives bring a certain degree of complexity with them because both objectives are linked to:

- The characteristics of the community where the HSCW is located:
  - The quantity and quality of the wastewater to be treated.
  - The climate.
- The design of the HSCW and the configuration of the WWTP.
- The ecological state of the receiving media.

Such degree of variation in the characteristics of HSCWs confirms the lack of consensus in the design of these WWTPs as well as the ignorance surrounding this technology's long-term operational capacities [EPA (1992), EPA (1993), Core Group (2000) and Kadlec *et al.* (2000)]. This is due to the fact that, beyond defining models for an optimal design, this variability also leads to the existence of a wide range of HSCWs, all of which are valid in the treatment of wastewaters, but have operation and maintenance needs which vary with each case, and which limit our ability to envisage the useful life of these systems.

As a result, the environmental problem to be solved was identified as:

Guaranteeing the correct operation of the HSCW proposed within the PSARU 2002 project through the definition of operation and maintenance tasks appropriate to the characteristics of each WWTP.

After the environmental problem had been identified, it was then defined. In order to guarantee the correct operation of an HSCW it is above all necessary to avoid problems arising. On occasion, despite the implementation of preventative actions, malfunctions may occur. In these cases, the problem must be identified and the most appropriate corrective actions taken to return the WWTP to its normal operational capacity. Operation and maintenance procedures must therefore include:

- **Preventative actions:** A series of activities which should be undertaken periodically in order to avoid problems arising.
- **Monitoring:** A series of measures to be carried out in order to verify the state of the HSCW and to detect possible problems as early as possible. The monitoring process also includes those measures to be carried out once a problem has been detected. These measures serve to identify the original cause of the problem when different causal factors are involved.
- **Corrective actions:** Actions to be carried out once the problem has been detected, and which allow the WWTP to return to its normal operational capacity (free from problems).

The reasoning followed to identify the environmental problem led to the discovery that the terms to be included in the operation and maintenance protocols varied with regard to the characteristics of the community, the design and configuration of the treatment plant, and the environmental state of the receiving media. Hence, the following data were required in order to develop the EDSS-maintenance prototype:

1) The characteristics of communities with fewer than 2,000 inhabitants which have to treat their wastewater using an HSCW.
2) The characteristics of the WWTPs which base their treatment on HSCW technology.

3) The ecological state of the receiving media into which the WWTPs spill the treated wastewater.

4) Identification and characterization of problems associated with an HSCW.

The EDSS developed for selecting the most appropriate treatment system (EDSS-treatment) provided a database with the characteristics of the communities which allowed us to define both (1) the quantity and the quality of the wastewater to be treated, and (2) the climatology of the WWTP's location. This EDSS also had another database containing the characteristics of the receiving media, information which was valid when used to define its quality.

Although the proposal for the best treatment alternative for EDSS-treatment facilitated WWTP configuration, the design for the HSCW to be constructed was still not available.

The possibility of reusing part of the research from the PSARU 2002 project and the results proposed for EDSS-treatment meant that the data and information necessary for construction of the EDSS-maintenance prototype were limited to the information which enabled identification and characterization of the problems associated with the HSCW in accordance with:

- The characteristics of the communities and receiving media taken from the database of the PSARU 2002 project.
- The configuration of the WWTPs as proposed by the EDSS-treatment.
- The design of the HSCW. As the HSCW design was unavailable, the selection was made to include all the possible design options defined in the bibliography and those defined by experts.

4.1.5. Recommendations to build the full EDSS-maintenance

The environmental problem analysis performed during the development of the EDSS-maintenance prototype allowed (1) characterizing the small WWTP domain; (2) identifying and characterizing the environmental problem and (3) defining the requirements to achieve an optimal solution. Although the conclusions derived from these three items can be extrapolated to develop the full EDSS-maintenance we recommended the repetition of this analysis before defining the other wastewater treatment technologies mainly to identify whether new water directives has appeared or not.

4.2. Data collection and knowledge acquisition

Following the environmental problem analysis we began to work on data collection and knowledge acquisition. This stage involved the eliciting, analysing and interpreting of data and knowledge that would allow us to propose operation and maintenance protocols according to the characteristics of HSCW systems.

4.2.1. Data and knowledge acquisition

The first development stage of EDSS-maintenance (4.1.4. Requirements for development of the EDSS-maintenance prototype) concludes that the data and knowledge necessary to construct the EDSS are those which allow the identification and characterisation of problems associated with HSCWs. This knowledge was obtained from the bibliographic research carried out in point 4.1.3. Horizontal subsurface constructed wetlands, the objective of which was to provide a reasonably detailed definition of HSCW technology: constituent elements of the system, treatment processes which take place, limitations, advantages and disadvantages. This approach to HSCWs (1) paved the way to a second bibliographic study focused on identifying and characterising the problems associated with this wastewater treatment technology (2) while facilitating the aforementioned identification and characterisation.

The second bibliographic study involved consultation of books on wastewater treatment technologies [i.e. Water Environmental Federation (1996), Alexandre *et al.* (1998) and Crites and Tchobanoglous (2000)], manuals on HSCWs [i.e. Cooper *et al.* (1996), the EPA(1999) and Kadlec *et al.* (2000)] and articles concerned with specific aspects of the operation and maintenance of this treatment technology [i.e. Blazejewski and Murat-Blazejewska (1997), Hygnstrom *et al.* (2002) and Thullen *et al.* (2002)]. The knowledge obtained from this second bibliographic study was of a general nature; however it did enable us to both (1) identify the main problems associated with an HSCW, and (2) form a primary characterisation of the latter. Using this knowledge, a questionnaire was produced in order to obtain knowledge concerning the experience of HSCW technology users in Catalonia. This survey was structured into 5 sections:

1) INVENTORY: The objective of the first part of the survey was to identify and characterise communities with a population of fewer than 2,000 inhabitants where wastewater is treated using HSCW technology, as well as to produce an initial description of these facilities:

    a. The location of the WWTP: The name of the community, region and province.

    b. The year of construction and starting date of the WWTP.

    c. Characteristics of the community: Number of inhabitants (fixed and seasonal), industrial activities and climate.

    d. A description of the WWTP site: Distances to the urban zone, surface area, land slope, altitude above sea level, etc.

    e. The WWTP set-up: Identification of pre-treatment, primary treatment, secondary treatment, and where applicable, tertiary treatment.

2) DESIGN: This second part of the survey focused on the description of each of the treatment system's different units (pre-treatment, primary treatment, secondary treatment and tertiary), placing special emphasis on HSCW technology.

3) CONTROL: In this section of the survey information was requested on the measures and checks carried out, as well as the frequency with which they are made, in order to obtain knowledge on the monitoring programmes for HSCW technology.

4) EXPLOITATION: The fourth stage of the survey asked about the operation and maintenance activities carried out, in order to identify and characterise the main problems associated with HSCW technology.

5) RECEIVING MEDIA: In the final section of the survey, questions were asked regarding the characteristics of the receiving media the treated wastewater is sent to.

These surveys were sent to the 13 HSWCs located in Catalonia (Figure 4.15), and were later completed and collected during visits to the facilities. During the first tour of visits made in June and July 2004, the first three points of the survey were completed (1. Inventory, 2. Design, and 3. Control), while the remaining sections (4. Exploitation and 5. Receiving Media) were completed during a second stage in September 2004 [Velayos *et al.* (2006)].

For each HSCW, a file was produced which summarised the results of the survey (Annex I – Questionnaire). Each file contained a total of 4 tables:

(a) The first table contains information on:

- Identification of the WWTP: Name of the community, the region to which it belongs and the year in which the facilities began operating.
- The WWTP set-up: Type of pre-treatment, primary treatment, secondary treatment and tertiary treatment. A diagram of the WWTP.
- A description of the site where the WWTP is located: The distance of the WWTP from the community and the receiving media, the surface area of the site, the distance of the WWTP from trees and/or bushes, altitude above sea level, the availability of electrical energy and the provision or absence of a perimeter fence.
- A description of the influent: Number of inhabitants, number of seasonal inhabitants, and a description of industrial activities.
- A description of the effluent: WWTP performance with respect to the elimination of suspended solids and organic matter (BOD_5 and COD).

(b) The second table presents the description – and in some cases photographs are provided – of the pre-treatment, primary treatment, secondary treatment and tertiary treatment. Where the HSCW acts as a tertiary treatment, the file describes the secondary treatment.

(c) The third table contains data referring to the design of the HSCW:

- A diagram of the HSCW.
- Characteristics of the cell: Length, width, depth, the slope of the cell bottom, exterior angle of the dikes, interior angle of the dikes, safety margin, covering and waterproofing and filling (diameter and thickness).
- Vegetation: Planted species, density of plantation and system of plantation.
- Water distribution and collection: Wastewater distribution system at entry, collection of treated water at exit, distribution system of water between the cells and the existence of *by pass* systems.

(d) The final table contains information on operation and maintenance of the WWTP:

- Visits to the WWTP: Frequency of visits and their objectives.
- Maintenance of vegetation: Frequency of vegetation control (cutting/mowing), removal of weeds and description of other aspects related to vegetation (diseases, fungi, etc.).
- Insects: Presence of insects and actions adopted.

- Rodents: Presence of burrowing animals and actions adopted.
- Water level: Water level measurement, when variations occur in the water level, degree of variation, and formation of surface flux.
- Distribution systems for sewage: Problems that occur, and how they are solved.
- Waterproofing layer: Problems that occur, and how they are solved.

Annex I – Questionnaire contains files for each HSCW; however, in a summarised form it may be established that [Velayos *et al.* (2006)] the 13 Catalan HSCWs are located in communities with between 350 to 1,500 inhabitants. Half of these towns experience seasonal variations in the number of inhabitants, either in the summer or at weekends. Half of them treat industrial wastewater from wine cooperatives, slaughterhouses, oil presses, sausage and cheese factories, etc. All of these industries generate wastewater which is similar to that of urban ones, and therefore assimilable by the HSCW.

These WWTPs are located on the coast or inland (Figure 4.15), at heights of under 675 m above sea level, which is the maximum altitude recommended in the PSARU 2002 project to avoid adverse meteorological conditions which could limit the performance of the HSCWs (at 646 m above sea level *Sant Martí Sesgueioles* is the highest WWTP).

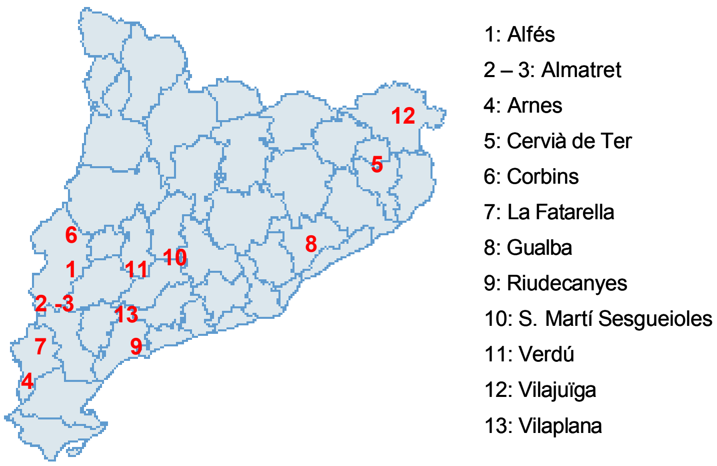

Figure 4.15. The location of HSCWs in Catalonia.

The sites where these HSCWs were constructed are a minimum distance of 300 m from the urban area, and have a surface area of between 20,000 m^2 and 4,000 m^2; however, in all cases there is room for expansion.

WWTP configuration includes (1) pre-treatment (i.e. thick screen, fine screen or grit removal unit), (2) primary treatment (i.e. septic tank, Imhoff tank or primary settler) and (3) secondary treatment (i.e. HSCW). While some facilities have tertiary treatment (i.e. free surface constructed wetland, waste stabilization pond, sand filter and plant soil treatment), in others the HSCW works as a tertiary treatment combined with other technologies (i.e. waste stabilization pond and high-rate pond) (Table 4.3).

HSCW systems are formed by two or more squared cells (working in series or in parallel), buried in the soil and protected with synthetic liners, except the HSCW in *Arnes* and *Vilajuïga*, which use compacted soil as waterproof material.

Table 4.3. Configuration of HSCWs operating in Catalonia.

Community	Pre-treatment	Primary treatment	Secondary treatment*	Tertiary treatment*
Alfés	Thick screen	Septic tank	HSCW	WSP
Almatret Nord	Thick-fine screen	Septic tank	HSCW	WSP
Almatret Sud	Thick-fine screen	Septic tank	HSCW	WSP
Arnes	Thick-fine screen	Imhoff tank	HSCW	FSCW
Cervià de Ter	Thick screen	Imhoff tank	HSCW	/
Corbins	Fine screen	Imhoff tank	HSCW	WSP HSCW SF
La Fatarella	Thick screen Grit removal	Primary settler	HSCW	WSP
Gualba	Thick-fine screen	/	HSCW	WSP
Riudecanyes	Thick screen Grit removal	Imhoff tank	HRP	HSCW
St. Martí Sesg.	Thick-fine screen	Septic tank	HSCW	/
Verdú	Thick screen	Septic tank	HSCW	WSP HSCW
Vilajuïga	Thick-fine screen	Primary settler	WSP	HSCW
Vilaplana	Fine screen	Primary settler	HSCW	PST

* HSCW: Horizontal Subsurface flow Constructed Wetland; HRP: High-Rate Pond; WSP: Waste Stabilization Pond; FSCW: Free Surface Constructed Wetland; SF: Sand Filter; PST: Plant Soil Treatment.

HSCW substrate is covered by large stones in the distribution and collection zones (diameter: 20-100 mm) and fine gravel in the central part (diameter: 2-20 mm) (Figure 4.16). Cell depth is around 0.6 m.

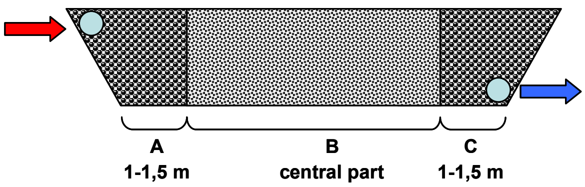

Figure 4.16. Gravel distribution in an HSCW: A and C (inlet and outlet zone); B (central part of cell).

Wastewater is distributed into the system by inlet structures (multiple-point discharge tubes or open channels) and collected by outlet structures (perforated tubes). The water level in the cells is regulated by adjustable riser pipes or valves.

The most common macrophyte is *Phragmites australis* (common reed), but *Typha angustifolia* (cattail) and *Scirpus holoschoemus* (juncos) can also be found in some HSCWs.

With the exception of *Arnes* all facilities are protected with a perimeter fence that discourages the entrance of unauthorised people and animals that could damage the plants and structures. Metal is the most common material for the fence but wooden fences or hedges are also used.

Plant managers at all HSCWs visited measure BOD_5, COD and suspended solids in the influent and effluent in at least once a month. pH (influent), total nitrogen and ammonium (influent and effluent) are also measured in some plants, but less frequently. Moreover, the Catalan Water Agency carries out fortnightly/monthly analyses of BOD_5, COD, suspended solids, conductivity, pH, total nitrogen, ammonium, total phosphorus, chloride and salts in almost all HSCWs.

Despite the fact that high removal levels are achieved for BOD_5 and COD (75 to 97 and 62 to 88%, respectively), Catalan HSCWs usually violate limits of pollutant concentration (25 mg/l BOD_5 and 125 mg/l COD) (Figure 4.17). The poor suspended solids removal efficiency (33 to 92%) is associated, in most cases, with a tertiary treatment consisting of a waste stabilization pond that increases suspended solids concentration in effluents. Figure 4.17 shows performance removal (columns) and effluent concentration (rows) at Catalan HSCWs during 2000-2003.

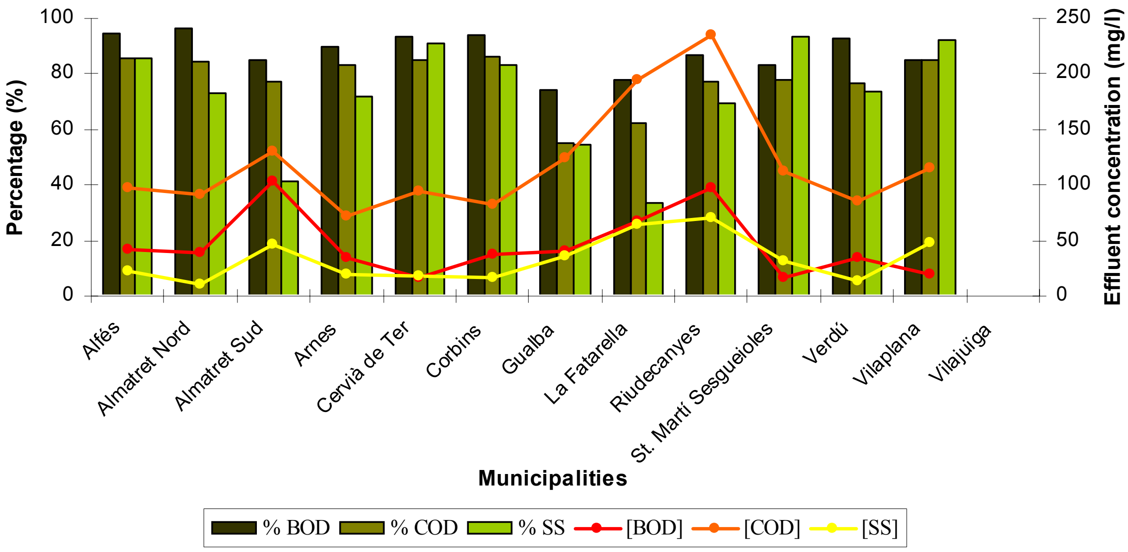

Figure 4.17. Performance removal and effluent concentration of SS, BOD_5, and COD in Catalan HSCWs.

In addition to this, at least once a week routine inspections are carried out to check the state of the vegetation, the wastewater distribution and collection systems, the water level, the presence of rodents, waterproofing properties and dike structure.

Routine maintenance tasks consist of cleaning the pre-treatment and the water distribution systems. In some facilities, weeds surrounding the treatment plant are also removed. Other maintenance tasks such as vegetation cutting, replanting or weed removal from the surface of the HSCW are done less frequently. In general, the vegetation is cut once a year, and after that weeds are removed from the surface. Some actions are carried out only when a deficiency is observed.

Table 4.4 shows the list of problems and their incidence level in Catalan HSCWs. Problems can be classified according to how they affect system performance. Problems from 1 to 14 have repercussions for treatment efficiency, 15 and 16 do not.

As shown in Table 4.4, the most frequent problems are related to vegetation cover, substrate clogging, water level and structures (dikes and waterproofing). Even though weeds growing on the surface of the HSCW is also one of the most frequently experienced problems, it is not considered a serious one in Catalonia and in many cases weeds are therefore removed just once a year (after vegetation cutting) or simply not removed at all.

Table 4.4. Main problems and their incidence level in Catalan HSCWs.

Problem (incidence)	
1 - Abnormal vegetation growth (0 %)	9 - Substrate clogging (46.2 %)
2 - Inappropriate vegetation density (30.7 %)	10 - Inappropriate water level (50.0 %)
3 - Accumulation of vegetation remains over the constructed wetland surface (7.6 %)	11 - Inappropriate water level controller regulation or maintenance (7.6 %)
4 - Weed growth (69.2 %)	12 - Unsuitable water distribution (23.1 %)
5 - Trees or bulrushes growth (7.6 %)	13 - Deficient waterproofing (69.2 %)
6 - Chlorosis (15.8 %)	14 - Deficient dikes structure (15.8 %)
7 - Presence of rodents (15.8 %)	15 - Bad smells (23.1 %)
8 - Presence of mosquitoes (15.8 %)	16 - Unsuitable fence and gate (30.7 %)

Substrate clogging is the most frequent problem in HSCWs. According to Cooper *et al.* (1996), substrate obstruction is caused by the accumulation of suspended solids in the porous matrix. In the Catalan HSCWs where this problem is detected, actions such as improving the pre-treatment and/or the primary treatment are recommended.

Clogging of inlet structures is a frequent problem, especially when multiple-point discharge tubes are used. Therefore, daily maintenance tasks are required. Some Catalan HSCWs are studying the possibility of substituting tubes for distribution channels, because the latter do not experience obstruction problems.

In previous studies [EPA (1999) and Crites and Tchobanoglous (2000)] the presence of rodents seemed much more relevant. Rodents are not frequent in Catalan HSCWs, however; they only appeared sporadically in a couple of treatment systems. The application of chemical products around the HSCW has been sufficient to deter these animals.

In the last section of the survey, questions were asked about receiving media in order to acquire knowledge of its state, sensitivity and usability. In general, ignorance of this item was observed and with the few obtained answers we can only differentiate three types of media: (1) land infiltration, (2) irrigation ditches or channels and (3) streams (which can be dry during some months of the year) or rivers (*Algars, Noguera Ribagorçana* and *Muga*).

4.2.2. Data and knowledge analysis

The volume of data and knowledge acquired for the development of EDSS-maintenance is highly inferior (249 objects) to that of other areas where the KDD process is applied (i.e. in astrological sciences the number of objects to be analysed is of the order of 10^9). This was one of the factors which led to the modification of the extraction process through knowledge defined by Fayyad *et al.* (1996) (3.2.2. Data and knowledge analysis), focusing it on a more traditional angle based on the analysis and the manual interpretation of the data and knowledge (Figure 4.18). The main differences between the two processes are: (1) the stages of data and knowledge selection and transformation are omitted and (2) the data mining is substituted by manual categorisation. Therefore, in the modified process all the data and preliminary knowledge are worked with, the format of this information is maintained throughout the research and the category or categories is/are assigned at the end.

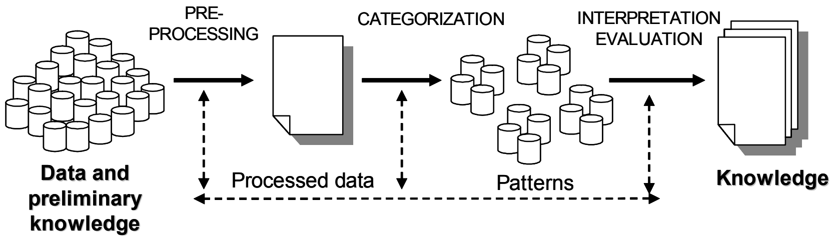

Figure 4.18. Process for obtaining knowledge from a database in accordance with the traditional method.

4.2.2.1. Pre-processing

In the data and preliminary knowledge stage all of the knowledge obtained in the bibliographic research was gathered together with that of the survey carried out in the 13 Catalan HSCWs. This information was processed by attempting to identify those aspects contemplated by the operation and maintenance protocol: mode, effects, causes, measures and controls, preventative measures and corrective measures. As a result of information processing, 24 problems (and the 24 respective modes) were identified as the most frequent disturbances in HSCWs. These abnormal situations are related to (1) vegetation growth, (2) water distribution, (3) the presence of rodents, (4) the state of the facilities, (5) weather conditions and (6) effluent quality. These problems result from (a) the characteristics of the influent, (b) the configuration and design of the WWTPs, (c) the characteristics of the community, (d) inadequate operation and maintenance and, sometimes, (e) the appearance of other disturbances. Overall, the knowledge base that has been constructed includes 58 potential causes. Furthermore, a total of 38 measures, 23 of which were needed to identify HSCW disturbances, were identified. 69 possible actions were defined; however, it was not feasible to define which of them are preventive and which are corrective, mainly because the described actions can be applied in both cases. Finally, 37 effects on the receiving media were identified.

Despite this method of organising the knowledge, certain difficulties were observed when it came to identifying and defining problems. For example, although some objects were considered problems by some HSCW experts, they could be considered as merely a cause (i.e. low environmental temperature) or as an effect (i.e. non-homogeneous distribution of water flow through the cells). Models used in the elaboration of this first group were therefore inconsistent – what is considered a problem, a cause, an effect…? These terms must be well defined.

Another fact which made the identification and definition of the problems difficult was terms with a different syntax but the same semantics being placed in different groups. For example, the term "Growth of weeds on the surface of the HSCW" was placed in the group of causes, and the term "Invasion of weeds" was considered to be an element of the group of problems, even though both terms have the same meaning: "The growth of plants which compete for space and nutrients with the planted macrophytes". Here we were able to see how one problem could simultaneously be the cause of another problem. Repeated terms were detected (the same semantics but with different syntax) in the groups of actions and problems, meaning that the application of certain actions may cause problems, and the same can be said for the groups of causes and effects, with the conclusion that the effects of some problems may be the cause of other problems.

Another point of ambiguity was localised in the characterisation of the measures to be taken in order to identify problems and the causes which provoke these malfunctions. The state of an HSCW may be determined through a series of measures, but the establishment of the frequency with which these have to be carried out and the expected results are aspects which are difficult to determine, as they vary with regard to the WWTP.

As well as making the identification and characterisation of each of the problems associated to an HSCW difficult, this muddling of terms also limited the definition of the relationships between the different problems which may take place in a WWTP of this type.

4.2.2.2. Categorization

In order to deal with the ambiguity observed in the processed data and knowledge, a methodology was required which would allow us to group the different terms we had identified into consistent, and at the same time flexible and adaptable groups. The objective was not to obtain models from a large volume of data, but to organise the knowledge into several previously defined groups. This necessity resulted in (1) the omission of the statistical techniques employed in the data mining process, and (2) the selection of a categorization as opposed to a classification. Although there are obvious similarities between classification and categorization, the differences have significant implications for the constitution of an information environment. While traditional classification is rigorous in that it dictates that an entity either is or is not a member of a particular class, the process of categorization is flexible and creative and draws non-binding associations between entities [Jacob (2004)].

Categorization is the process of dividing the world into groups of entities whose members are in some way similar to each other. Recognition of resemblance across entities and subsequent aggregation of like entities into categories lead the individual to discover order in a complex environment [Jacob (2004)]. The categories themselves are not innate and must be acquired from experience [Frey (2005)], and this is how 6 categories were identified and defined before beginning categorisation. These 6 categories are the key terms for defining the protocols for operation and maintenance.

- PROBLEM: An unplanned deviation from a predefined standard or expectation caused by one or more unexpected events or factors.
- MODE: Manner in which a system may present a problem.
- EFFECT: A measurable or observable (beneficial or adverse) change in the environment produced by a cause or action.
- CAUSE: Events or factors that provide the generative force which causes a problem.
- MONITORING PROGRAMME: Continuous or repeated observations to determine the level of compliance with performance requirements and pollutant levels.
- ACTIONS: Something done to avoid the causes which create a problem or something to be done when a problem occurs.

With regard to categorisation, the number of problems associated with HSCWs was reduced from 24 to 18. The 5 problems which referred to adverse meteorological conditions (high temperature, low temperature, high evapotranspiration, high rainfall and strong wind) did not adapt to the definition elaborated for the PROBLEM category: these 5 terms could not be considered as problems because the causes which created them could not be identified, and these 5 terms became part of the CAUSE category. On a level with this change, 6 of the effects initially considered were omitted. The problem which referred to non-homogeneous distribution of wastewater through the bases also changed category and became part of the EFFECT category. The non-homogeneous distribution of wastewater, despite being a deviation from the standard operation of an HSCW, is always found to be the effect of a problem.

The rest of the changes made in the categorisation process did not represent a change of category, but meant that a term formed part of more than a single category:

- The PROBLEM category includes a total of 18 terms, 12 of which are also included within the CAUSE category. At the same time, 13 of these 18 problems are included within the category EFFECT, and one of these 13 problems is also found within the ACTIONS category.
- The CAUSE category includes a total of 49 terms, 12 of which are also included within the PROBLEM category, and one is even found in the EFFECTS category.
- The EFFECTS category includes 31 effects, 13 of which are also included within the PROBLEM category, and one in the CAUSE category.
- Finally, within the ACTIONS category there is one action which is found within the PROBLEM category.

As a consequence of the reduction in the number of problems associated with HSCWs, the MODE category went from 24 terms to 18. With regard to the MONITORING PROGRAMME category, the subjects assigned in the pre-processing stage were maintained.

The categorisation process was therefore accompanied by (a) category changes (6 terms changed category), and (b) the definition of terms with unique syntax semantics which belong to more than one category (19 of the objects belong to more than one category).

The final point of ambiguity regarding the definition of frequency of measures and results of measures was not solved through the categorisation process. In order to deal with this dilemma, information on the measures was compared in order to identify the factors which cause this variability. The results of these analyses gave the following conclusions:

- The frequency of measures is dependent upon the dynamics of the problem, the frequency with which it arises, and the social and environmental impact of the problem.
- The degree of environmental impact varies with regard to the sensitivity of the receiving media.
- The sensitivity of the receiving media is defined by the absorption capacity of pollutants in the receiving media and its use.

4.2.2.3. Interpretation and evaluation

The interpretation and evaluation stage for the results obtained from categorisation of acquired data and knowledge permitted the identification and definition of:

(a) The problems associated with an HSCW.

(b) The existing relationships between these problems.

(c) The frequency of measures taken.

(d) The reasoning process for defining the protocols using the defined categories.

In other words, the interpretation and evaluation stage provided the information necessary for defining the operation and maintenance protocols.

a) Problems associated with an HSCW:

The characterisation of the 18 problems associated with HSCWs (Table 4.5) is detailed below. For each problem {P_i} there is a definition of the effects {E_i}, the causes {C_i}, the measures {M_i} included in the monitoring programme, and the actions {AC_i}. It should be pointed out that this definition includes the frequencies of the measures (c) Frequency of the measures) and the modifications derived from the protocol validation process (4.5. Evaluation process).

Table 4.5. List of problems associated with HSCWs.

Problem
P1 – Abnormal vegetation growth during the start-up
P2 – Low density or non-homogeneous density of vegetation
P3 – Accumulation of plant debris in the HSCW area
P4 – Growth of weeds in the HSCW
P5 – Growth of trees and/or bushes in the HSCW area and/or the surrounding area
P6 – Chlorosis
P7 – Plague of rodents
P8 – Obstruction of the matrix pores and the clogging of the substrate
P9 – Water level too high – Formation of surface flow
P10 – Water level too low
P11 – Anomalies in the distribution systems and/or water collection
P12 – Anomalies in the water level controller mechanism
P13 – Anomalies in the waterproof layer
P14 – Anomalies in the dikes
P15 – Anomalies in the perimeter fence and the gate
P16 – Production of bad smells
P17 – High concentration of organic matter in the effluent
P18 – High concentration of suspended solids in the effluent

P1 – ABNORMAL VEGETATION GROWTH DURING THE START-UP

MODE: Deficient growth of *Phragmites australis* during the vegetation establishment phase [Brix (2003)] {MD1}.

EFFECTS: The deficient growth of *Phragmites australis* is seen as a reduction in the efficiency of the treatment [EPA (1999)] {P17 and P18}. According to Tousignant *et al.* (1999), this problem can also promote a low density or non-homogeneous density of *Phragmites australis* {P2}, and the growth of weeds {P4}.

CAUSES:

- **Organic overload {C1}:** According to Tousignant *et al.* (1999) an organic overload can have repercussions on the proper growth of the planted vegetation.

- **Low temperatures {C2}:** Seasonal and temperature changes affect the activity and the growth of the plants [Cooper *et al.* (1996), EPA (1999) and Colorado Department of Public Health and Environment (2002)]. According to research carried out at Purdue University, the minimum temperature which *Phragmites australis* can tolerate is 6 ºC. Below this temperature the plant enters into a state of latency [Mæhlum *et al.* (1995) and Wittgren and Mæhlum (1997)], a state in which growth slows down or is completely stopped until temperatures become favourable. If the temperatures fall below 0 ºC the risk of mortality to *Phragmites australis* increases [Brix (2003)].
- **High temperatures {C3}:** The HSCWs are also affected when the air temperature is high. According to research done at Purdue University the maximum temperature tolerated by *Phragmites australis* is 26 ºC. Above this temperature vegetation growth is limited, and in extreme cases it may produce the death of the plants.
- **High evapotranspiration {C4}:** Cooper *et al.* (1996) and the EPA (1999) consider high evapotranspiration to be a limiting factor for the adequate growth of the vegetation planted. Kadlec *et al.* (2000) add that a high and prolonged evapotranspiration may cause the death of the plants.
- **Heavy rainfall {C5}:** Cooper *et al.* (1996), the EPA (1999) and Brix (2003), among other researchers, state that heavy rainfall or long periods of rain may influence the correct growth of the vegetation planted.
- **Strong gusts of wind {C6}:** Strong gusts of wind may bend and damage the vegetation in the HSCWs.
- **Growth of weeds in the HSCW area {P4}:** According to the European Community (1990), Cooper *et al.* (1996), Hygnstrom *et al.* (2002) and Brix (2003), weeds which grow in the HSCW area may compete with *Phragmites australis* for space and nutrients, a fact which makes the required establishment and development of the plant difficult.
- **Growth of trees and/or bushes in the HSCW area and/or surrounding area {P5}:** *Phragmites australis* is a plant which needs sun in order to grow, and therefore if there are bushes or trees around the HSCW or in the HSCW area, the resulting shade may cause growth difficulties for the macrophytes planted [Campdell and Ogden (1999), Hygnstrom *et al.* (2002) and Terraforms (2002)].
- **Plague of rodents {P7}:** According to Cooper *et al.* (1996), Campbell and Ogden (1999), the EPA (1999), the Core Group (2000), Crites and Tchobanoglous (2000) and Brix (2003) rodents may damage vegetation. They may eat seeds, tubers, rhizomes, young shoots and adult plants.
- **Inadequate water level {P9 and P10}:** A water level which is above or below the tolerance limits of *Phragmites australis* may cause the plant stress, which will negatively affect its growth [Kadlec *et al.* (2000)]. García *et al.* (2003) consider that a water level below that of the level recommended in the design may make establishment of the vegetation difficult.

MONITORING: The EPA (1999) recommends that the vegetation of the HSCWs is inspected various times a week during the period when the system is put into operation.

In Catalonia it is recommended to those HSCWs which deposit into a sensitive or highly sensitive receiving media that they carry out this check 2 or 3 times a week during the first year, and if the media is resistant, a weekly control is recommended during the first year {M1}. If any anomalies are observed in the growth of *Phragmites australis*, the causes should be identified in order to adopt the most appropriate measures.

- **Organic overload {C1}:** Crites and Tchobanoglous (2000) recommend measuring the BOD_5 of the influent before constructing the plant. This measure allows estimation of the organic load to be treated during operation (X_1 Kg $BOD_5 \cdot m^{-2} \cdot day^{-1}$: X_1 is the estimate of the organic load which must be treated by the HSCW per surface unit). Tousignant *et al.* (1999) and Crites and Tchobanoglous (2000) recommend measuring the BOD_5 of the influent and the effluent every week when the plant is starting operations. This control helps to detect problems of organic overload.

In order to verify whether the vegetation growth problems during the initial operational stages of the system are caused by an organic overload, it is recommended that the BOD_5 of the influent {M2} is measured, as well as the water flow entering the WWTP {M3}. If this check registers a BOD_5 above X_1 Kg $BOD_5 \cdot m^{-2} \cdot day^{-1}$, a reduction of the organic load to be treated is suggested, following some of the proposals detailed in the point **Reduction of the organic load {AC1, AC2 and AC3}** in the **ACTIONS** section. Some of the actions detailed in this point, such as the progressive increase in the organic load to be treated, may be applied in a preventative form.

- **Low temperatures {C2}:** Campbell and Ogden (1999) recommend measuring air temperature with a thermometer (Figure 4.19). If this measurement cannot be taken, qualitative type observations are accepted (i.e. solar radiation, intense light, occasional clouds, partially cloudy or cloudy).

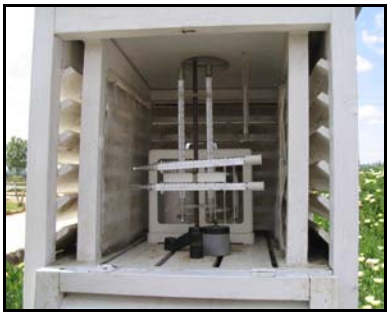

Figure 4.19. Detail of a meteorological station in the experimental water treatment plant in Carrión de los Céspedes (Andalusia). This meteorological station houses a thermometer and a thermohygrometer.

In order to verify whether the temperature is the cause of deficient vegetation growth, measuring or estimating the temperature is recommended {M4}. If the temperature is below 6 ºC the deficient growth of *Phragmites australis* may be associated with low temperature. In the research carried out no action has been found to deal with this problem.

- **High temperatures {C3}:** Campbell and Ogden (1999) recommend measuring air temperature with a thermometer (Figure 4.19). As in the case above, if this measurement cannot be taken, qualitative type observations are accepted (i.e. solar radiation, intense light, occasional clouds, partially cloudy or cloudy).

In order to verify whether high temperature is the cause of deficient growth, temperature measurement or estimation is recommended {M4}. If the temperature is above 26 ºC, measuring the water level is recommended {M5}. When it is necessary to increase the water level, the action **Increasing the water level {AC31}** is recommended, described in point P10 – Water level too low.

- **High evapotranspiration {C4}:** According to the EPA (1999) and the Core Group (2000), evapotranspiration is the sum of evaporation processes (water movement from the surface of the land into the atmosphere) and transpiration (the loss of water by plants). Evapotranspiration can be estimated from solar radiation and the wind; it may also be measured with an evaporimeter (Figure 4.20).

Figure 4.20. An evaporimeter at the experimental water treatment plant in Carrión de los Céspedes (Andalusia).

If the WWTP is equipped with an evaporimeter, measuring the evaporation is recommended, however if this is not possible, an estimation of evapotranspiration through the measurement of air temperature and/or solar radiation and the action of the wind is recommended {M6}.

If the measurements taken with the evaporimeter indicate a high level of evapotranspiration, or a high level of evapotranspiration is estimated from temperature measurements, solar radiation and/or wind measurements, measuring the water level is recommended {M5}. When it is necessary to increase the water level, the action **Increasing the water level {AC31}** is recommended, described in point P10 – Water level too low.

- **Heavy rainfall {C5}:** If the WWTP is equipped with a pluviometer (Figure 4.21), this equipment should be used to measure rainfall. If this equipment is not available, qualitative type measurements are recommended (i.e. intensity – zero, light rain, moderate rain, heavy rain, snow or hail – and the duration of the precipitation) {M7}.

Figure 4.21. Pluviometer at the experimental water treatment plant in Carrión de los Céspedes (Andalusia).

If a high rainfall has been measured or estimated, measuring the water level in the HSCWs is recommended {M5 and M25}. If the water level is above that recommended or there is surface flow, the action **Reducing the water level {AC29}** is recommended, as described in point P9 – Water level too high – Formation of surface flow.

- **Strong gusts of wind {C6}:** If the WWTP is equipped with an anemometer (Figure 4.22), this equipment should be used to measure the speed and direction of the wind. Where this equipment is not available qualitative type measurements are recommended (i.e. direction – north, south, east or west – and intensity – calm, breeze, moderate wind and strong wind –) {M8}.

If it is confirmed that the wind has damaged the planted vegetation, **Planting a tree screen {AC45}** is recommended to avoid the effect of the wind on the HSCW surface.

Figure 4.22. The red arrow shows the anemometer located on the evaporimeter at the experimental water treatment plant in Carrión de los Céspedes (Andalusia).

- **Growth of weeds in the HSCW area {P4}:** In order to verify whether the problem {P1} has been caused by the growth of weeds in the HSCW area, it is recommended that the measurements detailed in P4 –Growth of weeds in the HSCW area are taken, and that the actions recommended in this point are implemented if necessary.

- **Growth of trees and/or bushes in the HSCW area or the surrounding area {P5}:** In order to verify whether the problem {P1} has been caused by the growth of trees and/or bushes, it is recommended that the measurements detailed in P5 – Growth of trees and/or bushes in the HSCW area and/or the surrounding area are taken, and that the actions recommended in this point are implemented if necessary.

- **Plague of rodents {P7}:** To verify whether the problem {P1} has been caused by rodents, it is recommended that the measurements detailed in P7 – Plague of rodents are taken, and that the actions recommended in this point are implemented if necessary.

- **Inadequate water level {P9 and P10}:** To verify whether the cause of the problem {P1} is an inadequate water level, it is recommended that the measurements detailed in P9 – Water level too high – Formation of surface flow and P10 – Water level too low are taken, and that the actions recommended in these points are implemented if necessary.

Regarding the causes, as well as the actions proposed to solve the growth problems of *Phragmites australis*, preventative actions are indicated to promote the growth of the vegetation planted in the point **Other actions to promote the growth of *Phragmites australis* {AC4}**. On the other hand, if the *Phragmites australis* dies, for whatever reason, the recommended steps are (1) to remove the remains of the plant from the HSCW area in accordance with that detailed in the action **Removing the plant debris accumulated in the HSCW area {AC6}** in point P3 – Accumulation of plant debris in the HSCW area and (2) to programme the season for replacing the damaged plants in order to carry out the action **Replanting the vegetation cover {AC5}** as detailed in point P2 – Low density or non-homogeneous density of vegetation.

ACTIONS:

- **Reduction of the organic load:** García [Oral communication (2006)] recommends that the HSCW operate with water with a low loading. It is better to treat a greater flow and more diluted water than concentrated water and a weak flow (even though in the end the flow mass applied is the same). If the HSCW has to treat an influent with a high organic load, two types of actions are proposed: a progressively increasing the organic load to be applied [Tousignant *et al.* (1999) and Core Group (2000)] and diluting the influent [Crites and Tchobanoglous (2000)].

◊ Dilution with clean water {AC1}: Tousignant *et al.* (1999) recommend that during the first month after planting *Phragmites australis* the system should operate with clean water or wastewater with a low organic load. During the fifth week they recommend increasing the load to be treated to 50% of the prescribed load. During the following three months they propose gradually increasing the load until the total load is reached four months after plantation. The Core Group (2000) also recommend beginning the watering with clean water, and once the plants are established (a season of growth, or until the plants sprout, and therefore once the roots have recovered from transplantation), a dilution of clean water and wastewater. The proportion of wastewater will be progressively increased until watering can finally be carried out with wastewater alone. According to the Core Group (2000), following these steps reduces the stress caused by organic overload on the plants.

◊ Recirculation {AC2}: In order to reduce the organic load applied to an HSCW, Crites and Tchobanoglous (2000) propose a scaled feeding of the entry waters, combining these flows with previously treated wastewater from recirculation. Crites and Tchobanoglous (2000) state that the capacity for partial or complete recirculation in a reverse direction towards the entrance of the HSCWs is an action which facilitates a reduction in the concentrations of organic and solid materials in suspension, providing more oxygen to the entrance point, and improving the general performance of the these systems.

◊ Previous treatment {AC3}: Blazejewski and Murat-Blasjewska (1997) and Crites and Tchobanoglous (2000) propose carrying out preliminary treatments so that the influent which arrives at the HSCW does not have a high load of organic material or solids in suspension. Bécares (2004) recommends that all the HSCW should undergo primary treatment in order to avoid clogging of the system, and propose septic tanks, Imhoff tanks or anaerobic pools as more adequate systems. Arias and García [Oral Communication (2006)] propose the installation of a physical and chemical treatment as primary treatment. Vymazal (2002) goes a little further, and recommends installing a primary treatment which must be maintained and controlled in order to ensure that it operates correctly.

Firstly, the HSCW must be checked to verify as to whether a treatment has previously been installed. If a treatment has not been installed, installation is recommended. If the WWTP is already equipped with this primary treatment, checks must be made to verify that the operation and maintenance protocols are fulfilled. If they are not fulfilled they must be done, and if they are, fulfilled the option of modifying or extending the treatments will be considered.

- **Other actions to promote the growth of *Phragmites australis* {AC4}:** Tousignant *et al.* (1999) propose purchasing certified seed free from weed seeds, and increasing the density of *Phragmites australis* so that it can compete with the invading plants more effectively.

- **Planting a tree screen {AC45}:** A line of trees acts as a screen and reduces the effects of the wind on the HSCW. Care must be taken in planting a tree screen near the HSCW cells because plant debris may enter the HSCW (P3 – Accumulation of plant debris in the HSCW area) and roots may damage the HSCWs' waterproof layer and dikes (P5 – Growth of trees and bushes in the HSCW area and/or surrounding area).

P2 – LOW DENSITY OR NON-HOMOGENEOUS DENSITY OF VEGETATION

MODE: Reduction of the density of *Phragmites australis* (density below 4 units per m^2) or non-homogeneous plant covering (existence of patches without vegetation (Figure 4.23)) {MD2}.

Figure 4.23. HSCW with patches without *Phragmites australis*.

EFFECTS: The macrophytes of an HSCW intervene in the stabilisation of the substrate and the regulation of the flow; they promote the deposit of suspended solids, incorporate organic material, nutrients and trace elements, and transfer gases between the atmosphere and the matrix [Lara and Salgot (1999)]. They also play an important role in winter as they act as insulators against the cold [EPA (1999) and Kadlec *et al.* (2000)] and reduce the effects of wind [EPA (1999)]. This means that the lack of surface area covered by plants, or a density of plants below that recommended may result in a reduction in treatment efficiency {P17 and P18}.

CAUSES:

- **Organic overload {C1}:** In the Catalan HSCWs, a low density of vegetation in the areas close to the distribution point is associated with an organic overload.
- **Low temperatures {C2}:** Seasonal and temperature changes affect the activity and growth of the plants [Cooper *et al.* (1996), EPA (1999) and Colorado Department of Public Health and Environment (2002)]. According to research carried out at Purdue University, the minimum temperature *Phragmites australis* can tolerate is 6 ºC. Below this temperature the plants enter into a state of latency [Mæhlum *et al.* (1995) and Wittgren and Mæhlum (1997)], a state in which growth slows down or is completely stopped until temperatures become favourable again. If temperatures fall below 0 ºC the risk of mortality to *Phragmites australis* increases [Brix (2003)].
- **High temperatures {C3}:** HSCWs are also affected when the air temperature is high. According to research from Purdue University the maximum temperature tolerated by *Phragmites australis* is 26 ºC. Above this temperature vegetation growth is limited, and in extreme cases it may cause the death of the plants.
- **High evapotranspiration {C4}:** Cooper *et al.* (1996) and the EPA (1999) consider high evapotranspiration to be a limiting factor for the adequate growth of the vegetation planted. Kadlec *et al.* (2000) add that a high and prolonged evapotranspiration may cause the death of the plants.
- **Heavy rainfall {C5}:** Cooper *et al.* (1996), the EPA (1999) and Brix (2003), among other researchers, state that heavy rainfall or long periods of rain may influence the proper growth of the vegetation planted.
- **Strong gusts of wind {C6}:** Strong gusts of wind may bend and damage the vegetation in the HSCWs.
- **Density of plantation inferior to that recommended {C7}:** The EPA (1999) says that in some cases, and in order to lower construction costs, the density of the plantation is reduced. This action slows down the establishment of the plant cover (2 years are needed instead of one).
- **Deficient vegetation growth during the start-up {P1}:** Deficient establishment of vegetation during the initial operations period of the system promotes both a lower density of *Phragmites australis* [Tousignant *et al.* (1999)] and the formation of patches without plants.

- **Growth of weeds in the HSCW area {P4}:** According to the European Community (1990), Cooper *et al.* (1996), Hygnstrom *et al.* (2002) and Brix (2003), weeds which grow in the HSCW area may compete with *Phragmites australis* for space and nutrients, a fact which makes the required establishment and development difficult.

- **Growth of trees and/or bushes in the HSCW area and/or surrounding area {P5}:** *Phragmites australis* is a plant which needs sun in order to grow, and therefore, if there are bushes or trees around the HSCW or in the HSCW area, the resulting shade may cause growth difficulties for the macrophytes planted [Campdell and Ogden (1999), Hygnstrom *et al.* (2002) and Terraforms (2002)].

- **Plague of rodents {P7}:** According to Cooper *et al.* (1996), Campbell and Ogden (1999), the EPA (1999), Core Group (2000), Crites and Tchobanoglous (2000) and Brix (2003), rodents may damage vegetation. They may eat seeds, tubers, rhizomes, young shoots and adult plants.

- **Water level too high {P9}:** According to Kadlec *et al.* (2000) a water level less than 5 cm from the surface, or the existence of water above the surface of the HSCW may favour the formation of patches without plants and/or a low density of *Phragmites australis*.

- **Water level too low {P10}:** Kadlec *et al.* (2000) consider that the stress caused by a water level which is too low may favour a low density of *Phragmites australis* and/or the appearance of patches without plants.

- **Non-homogeneous water distribution {E1}:** In the Catalan HSCWs zones have been observed where the plant cover has been difficult to establish. This has been associated with non-homogenous distribution of water to the cells (Figure 4.24).

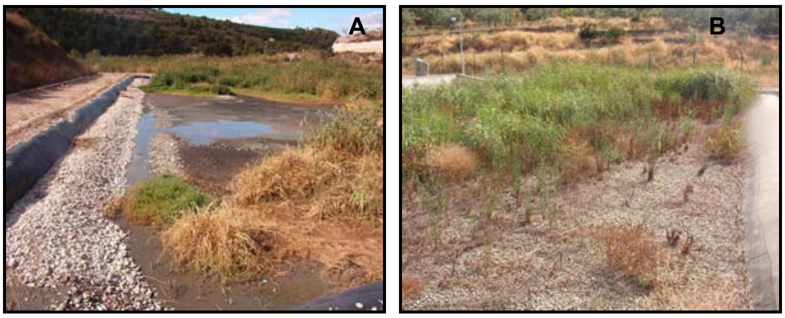

Figure 4.24. Non-homogeneous distribution of the vegetation:
A) Patch of plants close to the water inlet point of the HSCW, and
B) Patch of plants in another part of the HSCW.

MONITORING: Tousignant *et al.* (1999) recommend weekly inspections in order to verify the state of the plant cover. Crites and Tchobanoglous (2000) and Hygnstrom *et al.* (2002), propose that these inspections must be made once every three months.

Weekly visits are recommended for the HSCWs in Catalonia {M13}. Visits are also advisable after periods of rainfall, frost and strong winds. If during these visits there is evidence that the density of the plants has diminished and/or areas of the surface are seen to be without plant cover, it is recommended that the vegetation be replanted as indicated in the action **Replanting the plant cover {AC5}**, and the causes be identified in order to take more specific actions. In order to verify the density of the plants, Kadlec and Knight (1996) recommend doing transects.

- **Organic Overload {C1}:** As detailed in point P1 – Abnormal vegetation growth during start-up Crites and Tchobanoglous (2000) recommend measuring the BOD_5 of the influent before constructing the plant, thus estimating the organic load which is to be treated during the phase of use (X_1 Kg $BOD_5 \cdot m^{-2} \cdot day^{-1}$).

  In order to verify whether the lower density or the non-homogeneous density of *Phragmites australis* is due to an organic overload, it is recommended that the BOD_5 of the influent {M2} is measured, as well as the water flow entering the WWTP {M3}. If a BOD_5 measurement of above X_1 Kg $BOD_5 \cdot m^{-2} \cdot day^{-1}$ is taken, it is recommended that the organic load to be treated is reduced, following the action **Recirculation {AC2}** or the action **Previous treatment {AC3}**, both described in point P1 – Abnormal vegetation growth during start-up. If the HSCW has been in operation for less than a year, the action **Dilution with clean water {AC1}** may also be applied, which is also described in point P1 – Abnormal vegetation growth during start-up.

- **Low temperatures {C2}:** Campbell and Ogden (1999) recommend measuring air temperature with a thermometer (Figure 4.19). If this measurement cannot be taken, qualitative type observations are accepted (i.e. solar radiation, intense light, occasional clouds, partially cloudy or cloudy).

  In order to verify whether the temperature is the cause of the deficient growth of the vegetation, measuring or estimating the temperature is recommended {M4}. If the temperature is below 6 ºC the deficient growth of *Phragmites australis* may be associated with low temperature. In the research carried out no action has been found to deal with this problem.

- **High temperatures {C3}:** Campbell and Ogden (1999) recommend measuring air temperature with a thermometer (Figure 4.19). As in the case above, if this measurement cannot be taken, qualitative type observations are accepted (i.e. solar radiation, intense light, occasional clouds, partially cloudy or cloudy).

  In order to verify whether high temperature is the cause of deficient growth, temperature measurement or estimation is recommended {M4}. If the temperature is above 26 ºC, measuring the water level is recommended {M5}. When it is necessary to increase the water level, the action **Increasing the water level {AC31}** is recommended, described in point P10 – Water level too low.

- **High evapotranspiration {C4}:** According to the EPA (1999) and the Core Group (2000) evapotranspiration is the sum of evaporation processes (water movement from the surface of the land into the atmosphere) and transpiration (the loss of water by plants). Evapotranspiration can be estimated from solar radiation and the wind, it may also be measured with an evaporimeter (Figure 4.20).

  If the WWTP is equipped with an evaporimeter, measuring the evaporation is recommended; if this is not possible, however, it is recommended that an estimation be made of evapotranspiration by measuring the air temperature and/or solar radiation and the action of the wind {M6}.

  If the measurements taken with the evaporimeter indicate a high level of evapotranspiration, or a high level of evapotranspiration is estimated from the temperature measurements, solar radiation and/or wind measurements, measuring the water level is recommended {M5}. When it is necessary to increase the water level, the action **Increasing the water level {AC31}** is recommended, described in point P10 – Water level too low.

- **Heavy rainfall {C5}:** If the WWTP is equipped with a pluviometer (Figure 4.21), this equipment should be used to measure rainfall. If this equipment is not available qualitative type measurements are recommended (intensity – zero, light rain, moderate rain, heavy rain, snow or hail – and the duration of the precipitation) {M7}.

If a high rainfall has been measured or estimated, measuring the water level in the constructed wetlands is recommended {M5 and M25}. If the water level is above that recommended or there is water flux on the surface, the action **Reducing the water level {AC29}** is recommended, as described in point P9 – Water level too high – Formation of surface flow.

- **Strong gusts of wind {C6}:** If the WWTP is equipped with an anemometer (Figure 4.22), this equipment should be used to measure the speed and direction of the wind. Where this equipment is not available qualitative type measurements are recommended (i.e. direction – north, south, east or west – and intensity – calm, breeze, moderate wind and strong wind –) {M8}.

  If it is confirmed that the wind has damaged the planted vegetation, **Planting a tree screen {AC45}** is recommended as described in point P1 – Abnormal vegetation growth during the start-up to avoid the effect of the wind on the HSCW surface.

- **Density of plantation inferior to that recommended {C7}:** In order to verify whether the cause of the low density or the non-homogeneous density of the vegetation is due to the plantation of fewer than 4 plants per m^{-2}, the WWTP archives must be consulted in order to check this data {M23}. If a density of plantation less than that recommended is confirmed, proceeding with the action **Replanting the plant cover {AC5}** is recommended.

- **Deficient vegetation growth during the start-up {P1}:** If the HSCW has been operating for less than a year, the measures detailed in point P1 – Abnormal vegetation growth during start-up are recommended to verify whether {P1} is the cause of the low density or non-homogeneous density of *Phragmites australis* in the HSCW. Where necessary, the actions detailed in this point are recommended.

- **Growth of weeds in the HSCW area {P4}:** In order to verify whether the problem {P2} has been caused by the growth of weeds in the HSCW area, the measurements detailed P4 –Growth of weeds in the HSCW area are recommended, and where necessary, the actions recommended in this point.

- **Growth of trees and/or bushes in the HSCW area and/or surrounding area {P5}:** In order to verify whether the problem {P2} has been caused by the growth of trees and/or bushes, the measurements detailed in P5 – Growth of trees and bushes in the HSCW area and/or surrounding area are recommended, and where necessary, the actions recommended in this point.

- **Plague of rodents {P7}:** To verify whether the problem {P2} has been caused by rodents, the measurements detailed in P7 – Plague of rodents are recommended, and where necessary, the actions recommended in this point.

- **Water level too high {P9}:** In order to verify whether the problem {P2} is caused by a water level which is too high, the measures detailed in P9 – Water level too high – Formation of surface flow are recommended, and where necessary, the actions recommended in this point.

- **Water level too low {P10}:** In order to verify whether the problem {P2} is caused by a water level which is too low, the measures detailed in P10 – Water level too low are recommended, and where necessary, the actions recommended in this point.

- **Poor water distribution {E1}:** In order to verify whether the cause of irregular and non-homogeneous growth of the vegetation derives from a non-uniform distribution of water, measuring the water level at different points of the cells is recommended {M5}. If a poor distribution of water is confirmed, it is recommended that the origin be identified by following the instructions in points P5 – Growth of trees and bushes in the HSCW area and/or surrounding area, P7 – Plague of rodents, P8 – Obstruction of the matrix pores and the clogging of the substrate and P11 – Anomalies in the distribution systems and/or water collection, as these problems are those which may cause poor water distribution. Where necessary, the actions recommended in these points is advisable.

ACTIONS:

- **Replanting the plant cover {AC5}:** The EPA (1999) recommends replanting if it has been observed that the vegetation does not meet the expected densities for correct system performance. Hygnstrom *et al.* (2002) also recommend substituting the damaged plants, or those which have died, as soon as possible.

  In Catalonia the replanting of plants has been carried out with bare roots (3 plants per m^2), using parts of the already established plants, or by burying the nodules of *Phragmites australis*, in order to grow a new plant. These two final methods of re-plantation represent economic savings, as new plants need not be purchased.

P3 – THE ACCUMULATION OF PLANT DEBRIS IN THE HSCW AREA

MODE: The accumulation of plant debris in the HSCW area [Russell (1999) and Georgia Department of Natural Resources (2002)]. This plant debris comes from the cutting of *Phragmites australis*, the vegetation planted and/or the vegetation surrounding the WWTP (Figure 4.25) {MD3}.

Figure 4.25. The accumulation of plant debris originating from the HSCW itself and vegetation from the surrounding area.

EFFECTS:

- **Clogging of the substrate {P8}:** A layer of organic material may be laid on the substrate surface, cover the pores and reduce the filtration process [Cooper *et al.* (1996)].

- **Bad smells {P16}:** The natural decomposition of the plant debris which has been accumulated in the HSCW area may cause bad smells [Crites and Tchobanoglous (2000)].

CAUSES: This problem, according to Crites and Tchobanoglous (2000), is due to the non-removal of plant biomass which falls naturally onto the HSCW after the cutting/mowing of the *Phragmites australis* cover itself, or from the surrounding vegetation {C8}.

MONITORING: Hygnstrom *et al.* (2002) recommend inspecting the vegetation in order to check if there is an excess of dead plant debris which has accumulated in the HSCW area. Despite this recommendation, they do not establish the frequency with which this is to be carried out. They also recommend that the water level should be measured when an excess of plant debris has been detected in the HSCW area.

Recommendations for the Catalan HSCWs include inspection of the accumulated vegetation in the HSCW area {M9}: (1) immediately after cutting, (2) during inspection in order to verify the state of the plant cover, and (3) in the autumn, when the leaves fall. If excessive accumulation of plant debris is detected during any of these checks, it is recommended that the debris be removed following the steps indicated in the point **Removing plant debris accumulated in the HSCW area {AC6}**. Measuring the water level is also recommended {M5 and M25}, and where necessary, the level is to be readjusted, following the points detailed in **Reducing the water level {AC29}** in point P9 – Water level too high – Formation of surface flow or in **Increasing the water level {AC31}** in point P10 – Water level too low.

ACTIONS:

- **Removing plant debris accumulated in the HSCW area {AC6}:** Crites and Tchobanoglous (2000) propose removing and burning the plant debris once cutting has been carried out, in order to eliminate plant debris, and the EPA (1999) and Crites and Tchobanoglous (2000) propose shredding the debris to make fertiliser. Molle [Oral communication (2004)] also suggests two alternatives for plant debris, either burning or composting. The choice of one option or another depends on the area, and as in agricultural areas farmers often use other systems for fertilisation, the plant debris should be burned.

  In Catalonia plant debris produced during the cutting period is removed. Once the reeds have been cut, the debris is removed from the HSCW surface and is then (1) burned in the enclosure itself (in areas where and periods when fires can be lit), (2) placed in containers and transported to a dump, (3) taken to nearby land where it is left to dry, or (4) transported to compost plants. However, no type of action is carried out to remove the leaves which have accumulated on the HSCW surface, and which come from vegetation in the surrounding area. The removal of plant debris may be undertaken manually using garden forks, or heavy machinery as shown in Figure 4.26. One system or another will be chosen depending on the availability of resources, and the size, configuration and design of the HSCW. Under no circumstances may plant debris be stored near the HSCW, as this may attract rodents.

Figure 4.26. Cutting the vegetation of an HSCW using heavy machinery.

P4 – GROWTH OF WEEDS IN THE HSCW

MODE: The growth of plants on the HSCW surface [Cooper *et al.* (1996), European Community (1990) and Hygnstrom *et al*. (2002)] which compete with *Phragmites australis* for space and nutrients (Figure 4.27) {MD4}.

Figure 4.27. Detail of an HSCW with weeds.

EFFECTS: Invading plants compete with *Phragmites australis* and impede their growth [European Community (1990), Cooper *et al.* (1996) and Hygnstrom *et al.* (2002)] {P1 and P2}. They may also reduce the efficiency of the treatment [Cooper *et al.* (1996)] {P17 and P18}.

CAUSES:

- **Density of plantation inferior to that recommended {C7}:** The EPA (1999) says that in some cases, and in order to lower construction costs, the density of the plantation is reduced. This action slows down the establishment of the plant cover (2 years are needed instead of one), promoting the proliferation of weeds.
- **Plants transported with soil {C9}:** Tousignant *et al.* (1999) state that the invading plants which grow on an HSCW may have been brought in the soil used in construction of the treatment unit.
- **Inadequate maintenance of the vegetation in the area surrounding the HSCW {C10}:** If appropriate maintenance of the plant cover surrounding the HSCW is not carried out (periodic cutting), the plants may progressively invade the surface of the HSCW.
- **Deficient vegetation growth during the start-up {P1}:** Tousignant *et al.* (1999) state that if a follow-up procedure on the HSCW plant cover is not conducted during the first year of operation, the system may be rapidly colonised by invading plants.

MONITORING: Taylor *et al.* (1998) suggest carrying out a weekly check to verify whether weeds have grown on the HSCW. Tousignant *et al.* (1999) recommend that the state of the vegetation should be supervised, above all during the first years of system operation, which is the period required for a dense plant cover to establish itself. If invading plants are observed during the visits, it is recommended that these plants be pulled up as soon as possible.

In Catalonia an inspection of the plant cover {M10} is recommended once a week in spring, once a fortnight in summer and autumn, and once a month in winter. If the existence of invading plants is detected during any of the checks, the action **Removing invading plants {AC7}** is recommended.

In order to verify whether the growth of invading plants is due to inadequate maintenance of the vegetation in the HSCW area, a visual check of the area is recommended {M11}. If the vegetation in the HSCW area is abundant, thick, high, etc. and has invaded or is growing in the HSCW area, cutting the vegetation is recommended (**Cutting the plant cover surrounding the HSCW {AC8}**).

If the HSCW has been operating for less than a year, the measures detailed in point P1 – Abnormal vegetation growth during start-up are recommended to verify whether {P1} is the cause of the growth of weeds on the HSCW. The actions proposed in this point are recommended where necessary.

In the bibliographical research undertaken, other actions have been identified to solve the problem of invading plant growth. These actions are described in the points **Application of chemical products {AC9}** and **Light flooding of the HSCW {AC10},** outlined below.

ACTIONS:

- **Removing the invading plants {AC7}:** Cooper *et al.* (1996), Taylor *et al.* (1998), Tousignant *et al.* (1999) and Hygnstrom *et al.* (2002) recommend removing the invading plants as soon as they are detected, as they will compete with the planted vegetation and will make the growth and establishment of the latter difficult. Hygnstrom *et al.* (2002) recommend removing the invading plants manually, and add that damaged or dead plants must be replaced as soon as possible. Stockpiling the plant debris near the HSCW must be avoided since this may attract rodents.
- **Cutting the plant cover surrounding the HSCW {AC8}:** Cutting the plant cover around the HSCW area is recommended when the plants invade the HSCW area. When cutting, care will be taken to ensure that plant stalks do not fall into the HSCW area, as these are plant debris which may increase the organic load and promote the clogging of the matrix. Stockpiling the plant debris near the HSCW must be avoided since this may attract rodents.
- **Application of chemical products {AC9}:** Tousignant *et al.* (1999) and Hygnstrom *et al.* (2002) suggest applying authorised chemical products in order to eradicate the proliferation of plants other than those planted on the surface of the HSCW. On the other hand Lara and Salgot (1999) and Tousignant *et al.* (1999) themselves advise against the use of herbicides to control the proliferation of invading plants because these products may damage the vegetation and the population of micro-organisms responsible for the depuration processes.
- **Light flooding of the HSCW {AC10}:** Taylor *et al.* (1998), Tousignant *et al.* (1999) and the Core Group (2000) suggest provoking a flood of between 2 to 5 cm in order to avoid the growth of weeds, although they warn that in order to carry out this action the planted macrophytes must have a height of between 8 to 12 cm. Brix (2003) recommends provoking an inundation of some 30 cm in order to avoid the proliferation of weeds, even though he states that *Phragmites australis* does not tolerate excessive or prolonged exposure to a high water level, above all during the period when the plants are being established. Green and Upton (1995) state that the water level may be increased by up to 20 cm.

  If the *Phragmites australis* vegetation is of the recommended height (8 to 12 cm), initiating a flood period of some 5 cm depth is recommended, (a) for 2 months (if using clean water) or (b) for 1 week (if using wastewater), in order to prevent the growth of weeds. It is recommended that the water level in the cells be increased with the help of the water level controller located at the outlet point.

In some of the HSCWs visited in Catalonia, invading plants were considered that did not harm the performance of the system, and these were left in the cells as they also participated in the purification process. In other systems these plants are removed immediately after cutting, when access to the HSCW area is easiest, and invading plants can be easily localised and pulled up.

P5 – GROWTH OF TREES AND/OR BUSHES IN THE HSCW AREA AND/OR SURROUNDING AREA

MODE: The growth of woody plants (trees and/or bushes) in the HSCW area or the surrounding area [Cooper *et al.* (1996), Core Group (2000) and Terraforms (2002)] (Figure 4.28) {MD5}.

Figure 4.28. Trees growing around a treatment plant.

EFFECTS:

- **Poor water distribution:** Whitney *et al.* (2003) state that the growth of roots increases the porosity of the substrate and creates preferential channels which promote the reduction of hydraulic retention time {E2} and hinder the homogeneous distribution of water {E1}.
- **The plants may create shade over the HSCW {P1 and P2}:** *Phragmites australis* is a plant which requires sun to grow, and if there are trees or bushes around the HSCW or in the HSCW area, the resulting shade will hinder the growth of the planted macrophytes [Campbell and Ogden (1999), Hygnstrom *et al.* (2002) and Terraforms (2002)].
- **Damage to the dikes {P14} and the waterproof layer of the HSCW {P13}:** Cooper *et al.* (1996), Campbell and Ogden (1999), the Core Group (2000) and Terraforms (2002) state that trees which grow near the HSCW may damage the dikes and the waterproof layer with their roots.

CAUSES: A cause of the growth of woody plants in the HSCW area or in the surrounding area can be inadequate maintenance of the plant cover {C11} or of the vegetation around the HSCW area {C12}. Furthermore, as indicated by Tousignant *et al.* (1999) the growth of trees and/or bushes may be provoked by a substrate which contains seeds {C9}.

MONITORING: Many researchers recommend inspecting the area of the HSCW and the surrounding area in order to check for woody plants [Taylor *et al.* (1998), EPA (1999), Core Group (2000), Hygnstrom *et al.* (2002) and Seabloom and Hanson (2003)]. However, only Taylor *et al.* (1998) specify the need for a weekly inspection in order to check for the growth of trees and/or bushes.

In order to control the growth of woody plants in the Catalan HSCWs a monthly inspection of the HSCW area and the surrounding area is recommended {M12}. If the growth of these woody plants is detected during the visit, the action **Removing the trees and/or bushes which grow around and/or in the HSCW area {AC11}** is to be initiated. As a preventative measure, establishing a grass (lawn type) cover on the dikes is recommended (**Plant cover on the dikes {AC12}**); this prevents the growth of trees and/or bushes on these structures.

ACTIONS:

- **Removing the trees and/or bushes which grow around and/or in the HSCW area {AC11}:** It is recommended that trees and/or bushes growing in an area where they are not wanted be removed as soon as possible. Stockpiling plant debris near the HSCW must be avoided, since this may attract rodents.
- **Plant cover on the dikes {AC12}:** The Core Group (2000) state that one way of avoiding the growth of trees near the HSCW is to keep the dikes of the HSCW cells covered with a dense, healthy layer of

grass which, as well as avoiding erosion, will also limit the establishment of woody plants (trees or bushes).

In some Catalan HSCWs in which the growth of tree-like plants has been observed in the HSCW area, the plants were removed as soon as they were detected. In other systems, however, this action has not been carried out because operators considered that the presence of woody plants in the HSCW area does not have a negative effect on the performance of the system.

P6 - CHLOROSIS

MODE: Chlorosis is revealed in the yellowing of the leaves of *Phragmites australis* (Figure 4.29) caused by a lack of chlorophyll. The appearance of yellow blotches begins with the youngest leaves and ends up extending to the entire plant [Cooper *et al.* (1996)] {MD6}.

Figure 4.29. *Phragmites australis* affected by chlorosis.

EFFECTS: The effects of chlorosis are the yellowing of leaves, followed by leaf loss and the death of the plant {E3}.

CAUSES:

- **Low organic load {C13}** in the wastewater treated [Cooper *et al.* (1996)].
- **Lack of nutrients {C14}**, mainly iron, but also other nutrients such as nitrogen or sulphur. This lack of nutrients may be caused by a low concentration or because these nutrients are available but not assimilable by the plant [Cooper *et al.* (1996)].
- **Poorly developed rhizomes {C15}** which limit the absorption of iron in a reduced state, mainly if the matrix is alkaline and nitrate is the main source of nitrogen for the plant [Cooper *et al.* (1996)].
- **Inadequate water level {P9 and P10}:** Hygnstrom *et al.* (2002) associate the appearance of chlorosis with an inadequate water level which will cause the stress of the plants.

MONITORING: Weekly visits are recommended to check the health of the plants and to verify whether they are affected by chlorosis {M14} [Tousignant *et al.* (1999) and Crites and Tchobanoglous (2000)]. If the problem is detected, the water level is to be checked {M5 and M25}, and when necessary the level is to be readjusted in accordance with the steps detailed in point P9 – Water level too high – Formation of surface flow or in point P10 – Water level too low. If the disease is not caused by an inadequate water level and the HSCW has been operational for less than 2 years, **Promoting the development of the roots {AC16}** is recommended. If the cause cannot be detected **Consulting a specialist {AC13}** or **Applying iron-**

based composts {AC14} is recommended, and if replanting is necessary, the selection of **"Iron-efficient" plants {AC15}** is suggested.

ACTIONS:

- **Consulting a specialist {AC13}:** Tousignant *et al.* (1999) propose consulting an expert in order to solve the problem of chlorosis. Hygnstrom *et al.* (2002) also recommend consulting a horticulturist or a plant specialist if the appearance of the chlorosis is not due to an inadequate water level.
- **Applying iron-based composts {AC14}:** Cooper *et al.* (1996) recommend superficial applications of low concentrations of iron-based composts such as iron sulphate. This action will improve the state of the plants in the most affected systems.
- **"Iron-efficient" plants {AC15}:** If it is predicted that conditions will be favourable for the appearance of chlorosis (influent with a low organic load, low iron concentration, alkaline conditions, etc.) Cooper *et al.* (1996) recommend selecting "Iron-efficient" plants, i.e. plants with a mechanism that provokes the development of siderespores to improve the process of absorbing iron from the medium.
- **Promoting the development of the roots {AC16}:** Lowering the water level is recommended during the initial operation of the system [Campbell and Ogden (1999) and Crites and Tchobanoglous (2000)] or at the beginning of autumn [Core Group (2000)] in order to promote the penetration and development of the roots. This is to be done with the aid of the mechanism for regulating the water level in the cells, and the water film should be kept at a level of between 20 to 30 cm below the surface of the matrix for approximately 15 to 30 days. This action is usually undertaken as a preventative measure during the first 2 years of HSCW operation.

P7 – PLAGUE OF RODENTS

MODE: The presence of rodents which dig beneath the ground in order to construct their burrows [Cooper *et al.* (1996), Campbell and Ogden (1999), EPA (1999), Lara and Salgot (1999), Core Group (2000), Crites and Tchobanoglous (2000), Georgia Department of Natural Resources (2002) and Hygnstrom *et al.* (2002)] {MD7}.

EFFECTS: The proliferation of these animals around the treatment plant may adversely affect the operational capacity of the HSCW because:

- **They may promote a poor distribution of the water entering the HSCW** [Crites and Tchobanoglous (2000)] {E1} as well as **a reduction in the hydraulic retention time** {E2}.
- **They may damage the plants {P1 and P2}:** They may eat seeds, young shoots and adult plants [Cooper *et al.* (1996), Campbell and Ogden (1999), EPA (1999), Core Group (2000), Crites and Tchobanoglous (2000) and Brix (2003)] (Figure 4.30).
- **The construction of their burrows may erode the structure of the dikes {P14} and/or damage the waterproof layer {P13}** [Campbell and Ogden (1999), Lara and Salgot (1999), EPA (1999), Core Group (2000), Crites and Tchobanoglous (2000), Georgia Department of Natural Resources (2002) and Hygnstrom *et al.* (2002)]. The Seattle Department of Planning and Development (2000) also states that they may **Damage the perimeter fence {P15}**.

Figure 4.30. Photograph of a rodent (O*ndatra zibethicus*) eating plants in an HSCW.
[Source: Higgins and Mitsch (2001)]

CAUSES:

- **Characteristics of the HSCW {C16}:** The HSCWs are WWTPs which in themselves are ideal areas for these animals: they provide refuge and are excellent areas for breeding [Core Group (2000) and Crites and Tchobanoglous (2000)].
- **Inadequate design of the dikes {C17 and C18}:** Slopes over 5:1 [Campbell and Ogden (1999) and EPA (1999)] and/or without a protection or rock barrier [EPA (1999) and Core Group (2000)].
- **Accumulation of debris in the HSCW surrounding area {C19}:** The accumulation of waste/debris from pre-treatment, primary treatment, plant cutting, weed removal, trees and/or bushes in the HSCW surrounding area may attract rodents.

MONITORING: Tousignant *et al.* (1999) suggest a weekly visit to verify the state of the dikes and check that they have not been damaged by rodents. Other signs which show evidence of the presence of these animals are tracks, droppings and holes in the waterproof layer.

A daily visit is recommended for the Catalan HSCW when the receiving media is very sensitive or sensitive, or a weekly visit if the receiving media is resistant {M15}. If during any of these visits the presence of rodents is detected, identifying the cause of their presence is recommended in order to be able to adopt the most appropriate actions.

- **Inadequate design of the dikes – Slope {C17}:** In order to check if the presence of rodents has been caused by the inadequate design of the dikes, it is recommended that the slope be checked {M16}. If the slope is over 5:1, the action **Reducing the slope of the dikes {AC17}** is recommended.
- **Inadequate design of the dikes – Protection {C18}:** In order to check if the presence of rodents has been caused by a lack of dike protection, it is recommended that these structures are checked for a layer of gravel or rocks {M17}. If the dike is not fitted with either of these protective measures, the application of one of the measures is recommended, following the steps detailed in the action **Providing the dikes with a layer of gravel or rocks {AC18}**.
- **Accumulation of debris in the HSCW surrounding area {C19}:** In order to verify whether the accumulation of debris in the HSCW surrounding area has caused the presence of rodents, a check is recommended to verify whether there is an accumulation of waste/debris in the different system units or in the surrounding area {M18}. If an accumulation of waste/debris is detected, the action **Avoiding the accumulation of debris in the HSCW surrounding area {AC19}** is recommended.

Whatever the cause of the presence of rodents in the HSCW, the following actions may also be applied: **Covering the burrows {AC20}**, **Trap and poison campaigns {AC21}** and **Fitting a wire net over the HSCW surface {AC22}.** In addition to the action proposed, the state of the plant cover should be verified (P1 – Abnormal vegetation growth during start-up and P2 – Low density or non-homogeneous density of vegetation) for the waterproof layer (P13 - Anomalies in the waterproof layer), for the dikes (P14 - Anomalies in the dikes) and for the perimeter fence (P15 - Anomalies in the perimeter fence and the gate), to check whether these animals have damaged them.

ACTIONS

- **Reducing the slope of the dikes {AC17}:** Campbell and Ogden (1999) and the EPA (1999) propose that the slope of the dikes should be 5:1 or less. These design characteristics prevent rodents from constructing lairs in the dikes.
- **Providing the dikes with a layer of gravel or rocks {AC18}:** The EPA (1999) and the Core Group (2000) establish the option of placing a layer of gravel or rocks in the dikes. This cover prevents rodents from constructing tunnels in the dikes.
- **Avoiding the accumulation of debris in the HSCW surrounding area {AC19}:** Plant debris and solid wastes eliminated in pre-treatment and primary treatment must be removed from the HSCW area to a suitable place, since this rubbish may attract rodents and produce bad smells.
- **Covering the burrows {AC20}:** Lara and Salgot (1999) and the Core Group (2000) propose sealing the entrances of the burrows with bentonite.
- **Trap and poison campaigns {AC21}:** Campbell and Ogden (1999), the EPA (1999) and the Core Group (2000) propose placing traps as a control measure in order to control rodent plagues. They also mention poison campaigns, although they advise against the latter as this measure requires a great deal of dedication and is not selective.
- **Fitting a wire net over the HSCW surface {AC22}:** The Core Group (2000) recommend using mechanical-type protection actions in order to deal with rodents. They recommend planting through wire net which, in addition to preventing rodents from building layers, will also stop them eating the tubers and rhizomes of the plants.

In Catalonia the presence of rodents in the HSCW is infrequent, although in some areas where these systems are located, the presence of small rodents has been detected, such as the field mouse (*Apodemus sylvaticus*) (Figure 4.31).

Figure 4.31. Photograph of a field mouse (*Apodemus sylvaticus*).
[Source: http://www.xtec.es/crp-elprat/medinatu/ratolic.html]

The presence of this small rodent in the HSCWs in Catalonia is evident from the damage caused to the waterproof layer. To solve the problem, rat poison has been applied around the cells and the membrane has been repaired (Figure 4.32).

Figure 4.32. Detail of a repaired hole made by rodents in a waterproof membrane.

P8 – OBSTRUCTION OF THE MATRIX PORES AND THE CLOGGING OF THE SUBSTRATE

MODE: Partial or total clogging of the substrate through the accumulation of solids in the matrix pores [Cooper *et al.* (1996), Blazejewski and Murat-Blasjewska (1997) and the Georgia Department of Natural Resources (2002)]. This problem is reported to occur mostly when soil is used as a filter medium [Sanford *et al.* (1995)] {MD8}.

EFFECTS:

- **Non-homogeneous distribution of the water entering the cells {E1}**.
- **Presence of water on the HSCW surface {P9}:** According to Sanford *et al.* (1995), Blazejewski and Murat-Blasjewska (1997) and Vymazal (2002), clogging of the substrate can be observed through the formation of pools on the HSCW surface.

CAUSES:

- **Organic solid deposits {C1 and P3}** on the constructed wetland surface, or in the substrate pores [Cooper *et al.* (1996)]. These organic solids may be plant debris from the HSCW itself or from the surrounding area; they may also proceed from an influent with an organic overload.
- **Accumulation of suspended solids {C20}:** Blazejewski and Murat-Blasjewska (1997) and the Georgia Department of Natural Resources (2002) state that a possible cause of substrate clogging is the accumulation of suspended solids in the inside the pores.
- **Matrix with small diameter pores {C21}** which are rapidly blocked [Blazejewski and Murat-Blasjewska (1997)].
- **Anomalies in the distribution systems and/or water collection {P11}:** Experience at the HSCWs in Catalonia and Denmark [Arias (Oral communication, 2006)] has shown that poor distribution of the water entering the gravel beds may induce matrix clogging.

Other processes which may be influential are:

- **The growth of micro-organisms {C24}** which are responsible for the treatment of the wastewater [Blazejewski and Murat-Blasjewska (1997)].

- **Chemical precipitation and deposition on the pores {C25}** [Blazejewski and Murat-Blasjewska (1997)].
- **Obstruction of the pores caused by the growth of rhizomes and roots {C26}**, which reduces the size of the pores and the hydraulic capacity of the substrate [Blazejewski and Murat-Blasjewska (1997), Campbell and Ogden (1999) and EPA (1999)].

In Catalonia the clogging of the substrate has been detected through the observation of flux on the surface; causes of this type of clogging are attributed to a high load of solids in suspension.

MONITORING: The EPA (1999) recommends regular visits to the system in order to detect any problem which may lead to substrate clogging.

At the Catalan HSCWs, daily inspections are recommended {M19} during the first months of system operation. When the system is functioning at full capacity and the receiving media is highly sensitive or sensitive, continuing daily visits are recommended. However, when the receiving media is resistant, weekly inspections are suggested. If any sign of clogging is observed during these visits, the recommendation is to identify the cause of the problem in order to apply the most appropriate corrective actions:

- **Organic solids deposits – Organic overload {C1}:** In order to verify whether the cause of the matrix clogging is the treatment of an influent with an organic overload, it is recommended that the BOD_5 of the influent be measured {M2}, as well as the water flow entering the WWTP {M3}. If a BOD_5 above X_1 Kg $BOD_5 \cdot m^{-2} \cdot day^{-1}$ is detected during this check, the following actions are recommended: **Previous Treatment {AC3}** and/or **Dosing the water intake {AC24}**. If the accumulation of suspended solids is superficial, **Raking {AC25}** is recommended. Arias [Oral communication (2006)] also recommends the action **Recirculation {AC2}.**

- **Accumulation of suspended solids {C20}:** In order to verify whether the clogging is due to a high concentration of suspended solids, it is recommended that the concentration of solids in the influent be measured {M21}, as well as the water flow which enters the WWTP {M3}. If the applied load of suspended solids is above that of X_2 kg de $SS \cdot m^{-2} \cdot day^{-1}$ (X_2: estimation of the suspended solids that the HSCW has to treat per surface unit, made during the design of the WWTP) one of the following actions is recommended: **Previous treatment {AC3}** and/or **Dosing the water intake {AC24}**. If the accumulation of suspended solids is superficial, **Raking {AC25}** is recommended.

- **Matrix with small diameter pores {C21}:** In order to determine whether the diameter of the matrix pores is too small, taking a sample of the substrate is recommended to verify whether the matrix complies with recommended specifications {M22}:
  - Inlet and outlet zones: Average effective diameter of gravel (D_{10}) 32 mm, porosity of 36-40 % and hydraulic conductivity (ks) of 10,000 to 50,000 $m^3 \cdot m^{-2}.day^{-1}$.
  - Central zone: Average effective diameter of gravel (D_{10}) 16 mm, porosity of 35-48 % and hydraulic conductivity (ks) of 1,000 to 10,000 $m^3 \cdot m^{-2}.day^{-1}$.

  If it is confirmed that the HSCW's problems have been caused by inadequate pore diameter, substituting this layer of substrate is recommended in accordance with the action **Replacing the substrate {AC26}**, with a layer which fulfils the specified requirements. If this action is not viable (it is highly expensive), the following actions are recommended: **Dosing the water intake {AC24}, Raking {AC25}** if the accumulation of solids is superficial and/or **Applying coarse gravel {AC27}** in the inlet and water distribution zone if the clogging occurs in this area.

- **Organic solid deposits – Accumulation of plant debris in the HSCW area {P3}:** In order to verify whether the clogging is due to an accumulation of organic material in the HSCW area, the measures indicated in P3 – Accumulation of plant debris in the HSCW area are recommended, and where necessary, the actions recommended in this point.

- **Anomalies in the distribution systems and/or water collection {P11}:** In order to verify whether the clogging is due to poor distribution of water, the measures indicated in P11 – Anomalies in the distribution systems and/or water collection are recommended, and where necessary, the actions recommended in this point.

The causes **Growth of micro-organisms {C24}**, **Chemical precipitation and deposition on the pores {C25}** and/or **Obstruction of the pores by the growth of rhizomes or roots {C26}** are difficult to identify. If the cause which has lead to the clogging cannot be identified **Dosing the water intake {AC24}, Raking {AC25}** (where the accumulation of solids on the surface is observed) and/or **Applying coarse gravel {AC27}** to the inlet and water distribution area (if the clogging occurs in this zone), are recommended.

Despite this proposal to identify and solve clogging problems, Arias and García [Oral communication (2006)] recommend taking no action as long as the effects of bad smells {M35}, the proliferation of mosquitoes {M37} and/or the low quality of the effluent {M27, M38 and M39} are not evident.

Whatever the original cause of the matrix clogging, if the degree of obstruction is high (over 75% of the surface is permanently stagnant) and the effects mentioned in the above paragraph are shown, studying the option of totally or partially replacing the substrate (**Replacing the Substrate {AC26}**) is recommended.

ACTIONS:

- **Dosing the water intake {AC24}:** Blazejewski and Murat-Blasjewska (1997), Taylor *et al.* (1998) and the Georgia Department of Natural Resources (2002) consider that one way of preventing, and/or solving clogging is to stage the entry of wastewater to the treatment system, i.e. a successive system of a feeding period followed by a drainage period.

- **Raking {AC25}:** In some Catalan HSCW where superficial clogging has been observed in the wastewater inlet and distribution area, the first 1 – 2 m of the bed were scraped using a small rake, in order to (1) remove the surface layer of accumulated solids, and (2) turn over the first few centimetres of the matrix surface, this action improves hydraulic conductivity of the substrate, and slows or prevent clogging. The best period for raking is after plant cutting as the action can be carried out easily, and with a decreased risk of damaging the planted vegetation. Care must be taken in order to ensure that roots are not damaged during the raking procedure. On some occasions after raking, new gravel has been transported to the treated areas.

- **Replacing the substrate {AC26}:** Where the substrate does not fulfil recommended specifications and needs to be replaced, or because the degree of blocking is inadequate, replacement must be carried out following the steps detailed in section 4.1. Environmental problem analysis (**Types of substrate** and **Substrate measurements**). It must be taken into account that this action is highly expensive as both substrate and vegetation must be removed. This solution is only recommended when no other alternative is feasible.

♦ **Applying coarse gravel {AC27}:** Blazejewski and Murat-Blasjewska (1997) recommend adding medium-sized or coarse gravel to the areas where clogging occurs. Mainly in the inlet zone in order to facilitate water distribution through the matrix. Arias [Oral communication (2006)] also recommends modifying the wastewater distribution area.

In Catalonia various actions have been carried out in order to solve localised clogging problems in the water inlet and distribution points:

- In some HSCWs, pebbles or medium-sized gravel have been added to the wastewater inlet and distribution area (**Applying coarse gravel {AC27}**).

- Another action which has been carried out is related to the positioning of the distribution tubes. The action consists of digging up the tubes and positioning the openings upwards, in this way the water distribution is improved while preventing the clogging of the matrix in the first few metres of the HSCW (P11 – Anomalies in the distribution systems and/or water collection). In the same way, in some HSCWs the water distribution system via a perforated tube has been substituted by a channel (**Improving the distribution systems {AC33}**).

- In addition, in some WWTPs the feeding surface has been raked in a preventative manner and immediately after cutting vegetation; this action eliminates the layer of accumulated mud and facilitates the distribution of water (**Raking {AC25}**).

P9 – WATER LEVEL TOO HIGH – FORMATION OF SURFACE FLUX

MODE: A water level is considered to be too high when the HSCW operates under normal conditions and the water level is less than 5 cm from the surface of the matrix. Formation of flux on the surface is considered to occur when, operating under normal conditions, part of the wastewater flows over the surface of the HSCW matrix [EPA (1999) and Lara and Salgot (1999)] (Figure 4.33) {MD9}.

Figure 4.33. HSCW with water on the surface.

EFFECTS: If the water level is too high (a) it will hinder the diffusion of oxygen from the atmosphere to the radical area inside the matrix {E4}, (b) it will hinder the growth of *Phragmites australis* [Kadlec *et al.* (2000)] {P1 and P2}, (c) it will induce the appearance of chlorosis [Hygnstrom *et al.* (2002)] {P6} and (d) induce the production of bad smells [Hygnstrom *et al.* (2002)] {P16}.

If the water level increases and there is water on the surface, the following effects may also occur:

- **Reduction in the efficiency of the treatment** [EPA (1999) and Vymazal (2002)] {P17 and P18}.
- **Reduction in water retention time** [Sanford *et al.* (1995)] {E2}.
- **The presence of mosquitoes** [EPA (1999)] {E5}.
- **Health risks** for people who may enter into contact with the wastewater [EPA (1999)] {E6}.

CAUSES:

- **Heavy rainfall {C5}:** The EPA (1999) considers that intense rainfall or long periods of constant rainfall may cause a temporary increase in the water level.
- **Clogging of the substrate {P8}:** A layer of organic matter may form on the surface of the granules, obstructing the pores and reducing the filtration process [Cooper *et al.* (1996) and Vandaele *et al.* (2000)]; this may cause the formation of flux on the surface. Sanford *et al.* (1995) relate flux on the surface with the accumulation of solids (organic and/or inorganic) in the substrate pores.
- **Anomalies in the water level controller mechanism {P12}:** The HSCWs are equipped with a mechanism to regulate the flow of water into the cells. If this mechanism has deteriorated or is not correctly regulated the water level in the cells may increase and there may even be a formation of flux on the surface.
- **Anomalies in the waterproof layer {P13}:** Terraforms (2002) state that the waterproof layer prevents the entrance of ground water into the HSCWs. Therefore, if the waterproofing does not fulfil its functions, and the water table layer is high, ground water may enter the constructed wetland.

MONITORING: Lara and Salgot (1999) recommend checking the HSCW for signs of surface flux, although they do not specify the required frequency of visits.

For HSCWs in Catalonia daily checks are recommended if the receiving media is sensitive or highly sensitive, or weekly checks when the receiving media is resistant. Checks are also recommended after periods of significant rainfall. These checks are to verify that there is no water on the surface {M25}; measuring the water level in the cells is also recommended {M5}. Lysimeters are necessary in order to carry out this measure (Figure 4.34). If these measuring instruments are not available at the plants, the installation of various instruments of this type, in accordance with the size and the shape of the cells, is recommended {AC28}.

Figure 4.34. Detail of a lysimeter.

If during any of these checks a water level above that recommended is found and/or water is observed on the surface, identification of the causes is recommended in order to take the most appropriate corrective actions.

- **Heavy rainfall {C5}:** If the WWTP is equipped with a pluviometer (Figure 4.21), this equipment should be used to measure rainfall. If this equipment is not available qualitative type measurements are recommended (intensity – zero, light rain, moderate rain, heavy rain, snow or hail – and the duration of the precipitation) {M7}.

  If a heavy rainfall has been measured or estimated, a water level which is too high or surface flux may be related to this cause. In this case **Reducing the water level {AC29}** is recommended. If the constructed wetland is equipped with a water intake dosage unit, the action **Dosing the water intake {AC24}** is also recommended (P8 – Obstruction of the matrix pores and the clogging of the substrate).

- **Clogging of the substrate {P8}:** In order to verify whether the increase in the water level and/or the formation of surface flux are due to a clogging of the substrate, the measures in P8 – Obstruction of the matrix pores and the clogging of the substrate are recommended, and where necessary, the actions recommended in this point.

- **Anomalies in the water level controller mechanism {P12}:** In order to verify whether the water level and/or the formation of surface flux are due to anomalies in the water level regulation mechanism the measures detailed in P12 - Anomalies in the water level controller mechanism are recommended, and where necessary, the actions recommended in this point.

- **Anomalies in the waterproof layer {P13}:** In order to verify whether the increase in the water level, and/or the formation of surface flux are due to anomalies in the waterproof layer, carrying out the measures detailed in P13 - Anomalies in the waterproof layer is recommended, and where necessary the actions recommended in this point.

If the HSCW is equipped with a reserve cell, whatever the cause of the problem, proceeding with the action **Using the reserve cell {AC30}** is recommended.

ACTIONS:

- **Reducing the water level {AC29}:** If the WWTP is equipped with a system which regulates the water level (Figure 4.36), reducing the water level until there is no longer any surface flux is recommended. Checks must be made to ensure that this variation in the water level does not cause a reduction in effluent quality {M27 and M39}.

- **Using the reserve cell {AC30}:** If the facility is equipped with a reserve cell, users may temporarily stop using the cell with surface flux problems and continue with treatment using the reserve cell [Campbell and Ogden (1999)].

P10 – WATER LEVEL TOO LOW

MODE: An excessively low water level is when the HSCW operates under normal conditions and the water level is more than 15 cm from the matrix surface {MD10}.

EFFECTS:

- **Reduction in hydraulic retention time {E2}:** In reducing the water level the effective volume is also reduced and therefore the hydraulic retention time is reduced.

- **The roots dry out {E7}:** Hygnstrom *et al.* (2002) state that during hot summers a low water level may cause roots and rhizomes to dry out.

- **Deficient growth of vegetation during the initial operation of the system {P1}:** Kadlec *et al.* (2000) and García *et al.* (2003) consider that poor establishment of the vegetation may be caused by a water depth below that recommended in the design. Molle [Oral communication (2004)] does not consider a temporary lack of water to be a problem for the vegetation in a system of this type, provided that this does not occur during the first operative year of the HSCW.

- **Low density or non-homogeneous density of vegetation {P2}:** Although some researchers [Molle (Oral communication, 2004)] consider that a low water level does not affect the plant cover, others [Kadlec *et al.* (2000)] consider that the stress caused by an excessively low water level may promote a low density of *Phragmites australis*.
- **Inducement of chlorosis {P6}:** Hygnstrom *et al.* (2002) associate the appearance of chlorosis to an inadequate water level which causes plants stress.

The five effects mentioned may cause a reduction in treatment efficiency {P17 and P18}.

CAUSES:

- **High evapotranspiration {C4}:** Water loss occurs with evapotranspiration (through the plants and/or the matrix surface). This water loss may reduce the water level in the cells, and as a consequence increase the hydraulic retention time and the concentration of pollutants [EPA (1988), EPA (1999) and Kadlec *et al.* (2000)].
- **Anomalies in the water level controller mechanism {P12}:** The HSCWs are equipped with a mechanism which regulates the water level in the cells. If this mechanism has deteriorated, or is not correctly regulated the water level in the cells may diminish.
- **Anomalies in the waterproof layer {P13}:** Imperfections and/or defects in the waterproof layer may mean that the layer loses its impermeable properties, i.e. it does not protect the treatment system, which may lead to infiltrations into the subsoil [Campbell and Ogden (1999) and Kadlec *et al.* (2000)], as well as a reduction in the water level in the cells.

MONITORING: In order to check whether the water level in the HSCWs in Catalonia is adequate, daily checks are recommended if the media is highly sensitive or sensitive, or weekly checks when the receiving media is resistant. The height of the water is measured in these controls {M5}. Lysimeters are needed to carry out this measure (Figure 4.34). The installation of lysimeters is recommended in those plants which are not equipped with these measuring instruments; various lysimeters should be fitted at different points on the cells, depending on the size and shape of the HSCW {AC28}.

If a water level below that recommended is found in any of these checks the causes should be identified in order to take the most appropriate corrective actions.

- **High evapotranspiration {C4}:** Evapotranspiration can be estimated from solar radiation and the wind, it may also be measured with an evaporimeter (Figure 4.20). If the WWTP is equipped with an evaporimeter, measuring the evaporation is recommended. If this is not possible, however, an estimation of evapotranspiration through a measurement of the air temperature and/or solar radiation and the action of the wind is recommended {M6}. If the measurements taken with the evaporimeter indicate a high level of evapotranspiration **Increasing the water level {AC31}** is recommended.
- **Anomalies in the water level controller mechanism {P12}:** In order to verify whether the water level and/or the formation of surface flux are due to anomalies in the water level controller mechanism the measures detailed in P12 - Anomalies in the water level controller mechanism are recommended, and where necessary, the actions recommended in this point.
- **Anomalies in the waterproof layer {P13}:** In order to verify whether the increase in the water level, and/or the formation of surface flux are due to anomalies in the waterproof layer, the measures detailed

in P13 - Anomalies in the waterproof layer are recommended, and where necessary, the actions recommended in this point.

ACTIONS:

♦ **Increasing the water level {AC31}:** Molle [Oral communication (2004)] proposes increasing the water level in the cells using the water level regulation mechanism for the water outlet (Figure 4.22), until the level recommended for routine situations is reached.

P11 - ANOMALIES IN THE DISTRIBUTION SYSTEMS AND/OR WATER COLLECTION

MODE: Faults and/or imperfections in the water distribution system in the HSCW, such as blockage of the holes in the distribution tubes (Figure 4.35, a), the accumulation of coarse pebbles in the channels or the inadequate design and/or construction of the constructed channel (Figure 4.35, b), which mean that the water is not uniformly distributed.

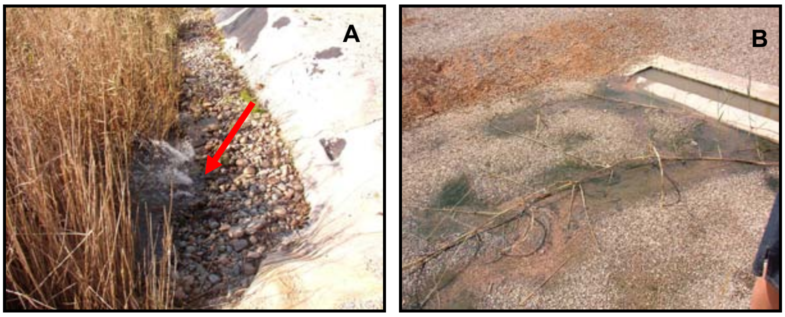

Figure 4.35. (A) Wastewater distribution tube with blocked holes. The red arrow shows the water release points. (B) Unlevelled water distribution channel.

EFFECTS: The main effect of the obstruction of the holes in the distribution tubes, and of an inappropriate design and/or construction of the constructed channel is a poor distribution of the water entering the cells {E1}. This may cause the non-homogeneous growth of *Phragmites australis* {P2}, induce the clogging of the matrix {P8}, etc.

CAUSES:

- **Accumulation of solids {C27}** transported by the wastewater, and which have not been eliminated in the pre-treatment [EPA (1999)].
- **Inadequate design and/or construction of the constructed channel {C28}.**
- **Formation of ice layers {C29}** which may damage the water distribution tubes [Mæhlum *et al.* (1995)].

MONITORING: In order to check the correct state of the water distribution systems, whether these are tubes or channels, an inspection of the systems is recommended to check that the tube holes are not blocked {M28} or that solids have not accumulated in the channels {M29}. This inspection should be carried out on a daily basis if the receiving media is highly sensitive or sensitive and on a weekly basis if the receiving media is resistant.

If during the inspection it is observed that the tube holes are blocked through the accumulation of solids inside the pipe {C27}, the action **Cleaning the water distribution tubes {AC32}** is recommended, in addition to taking into account the proposals in **Improving the water distribution systems {AC33}.** The action **Previous treatment {AC3}** is also recommended (P1 – Abnormal vegetation growth during start-up).

If an accumulation of suspended solids or coarse solids (plant debris, plastic, sand, etc.) is observed during any of the inspections {C27}, cleaning is recommended in accordance with the steps detailed in the point **Cleaning the water distribution channels {AC34}.** As in the case above, the action **Previous treatment {AC3}** is also recommended (P1 – Abnormal vegetation growth during start-up).

In order to detect whether the cause of the problem is due to the inadequate design and/or construction of the channel {C28}, a visual inspection of the channel is recommended {M24} and where necessary, the action **Restructuring the water distribution channel {AC35}.**

If the constructed wetland is located in an area which suffers from heavy frosts in winter, verifying the state of the water distributors is also recommended immediately after periods of intense cold, to check if ice has formed on the surface or inside the tubes, as this may damage them {M26}. If this is the case, the action **Cleaning the water distribution tubes {AC32}** is recommended.

ACTIONS:

- **Cleaning the water distribution tubes {AC32}:** The EPA (1999) states that it is necessary to extract the solids accumulated in the water distribution systems. The following steps are recommended: (1) unblock the tube holes as soon as blockages are observed, and (2) clean the inside of the tube, usually with a pressurised water jet in order to eliminate the materials which may have accumulated inside.
- **Improving the distribution systems {AC33}:** In some HSCWs in Catalonia actions have been undertaken to improve the residual water distribution systems:
  - ◊ In some HSCWs which have perforated underground tubes as their distribution system (Figure 4.35, a), the tubes have been uncovered and the holes have been positioned upwards. This set-up facilitates the cleaning of both the tube and the holes through which the wastewater is distributed; it also prevents the obstruction of the holes through the accumulation of solids.
  - ◊ Another improvement measure undertaken in some HSCWs is the substitution of the perforated tube distribution systems for other distribution systems. The system recommended is a constructed channel (Figure 4.35, b), as experience has shown that in these systems problems related to the accumulation of solids seldom occur.
- **Cleaning the water distribution channels {AC34}:** The cleaning of the water distribution channels consists of the removal of solids accumulated in the water distribution channel. This measure may be carried out manually with the use of rakes, spades, etc. The accumulation of solids removed from the channel must be avoided at all times as such waste material may attract rodents.
- **Restructuring the water distribution channel {AC35}:** This corrective measure is undertaken in order to level the water distribution channel. This measure can be carried out by either restructuring the construction or by fitting some type of mechanism (metal, plastic, cement, etc.) which serves to level the channel.

P12 - ANOMALIES IN THE WATER CONTROLLER MECHANISM

MODE: The water level controller mechanism is not properly regulated, or it may be defective in some way, i.e. corrosion on metallic parts (Figure 4.36) {MD12}.

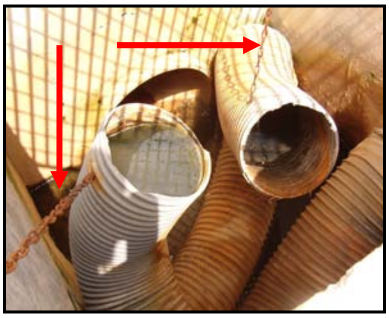

Figure 4.36. The water level controller mechanism flexible tube.
The red arrows show the rusty chains which hold the tubes.

EFFECTS: If the water level controller mechanism is defective, i.e. the system is incorrectly regulated, the effect observed will be an inadequate water level: a water level which is too high {P9}, the formation of surface flux {P9} or a water level which is too low {P10}.

CAUSES:

- **Inadequate maintenance of the water level controller mechanism {C30}:** The water level controller mechanism requires maintenance (i.e. anti-corrosion treatment, chain replacement, etc.) as constant contact with wastewater may accelerate deterioration of the system.
- **Inadequate regulation of the water level controller mechanism {C31}:** The incorrect regulation of the mechanism may lead to an incorrect water level.

MONITORING: In order to verify the correct state of the water level regulating mechanism an inspection of the device is recommended {M20}. This inspection should be carried out on a daily basis if the receiving media is highly sensitive or sensitive, and on a weekly basis if the receiving media is resistant. If a defect is found during the observation, repairs must be carried out (**Repairing or substituting the water level controller mechanism {AC36}**) as soon as possible.

In order to verify whether the water level controller mechanism is correctly regulated, the device should be checked with the lysimeters in the cells {M5} following the steps detailed in points P9 – Water level too high – Formation of surface flow and P10 – Water level too low. If the mechanism is not correctly adjusted, the actions **Reducing the water level {AC29}** or **Increasing the water level {AC31}** are recommended, as detailed in these points.

ACTIONS:

- **Repairing or substituting the water level controller mechanism {AC36}:** If the damage detected in the visual inspection is easily reparable, such as corrosion on the chain which holds the regulator pipes, repairs will be made. However, if the defects observed are serious, such as punctured pipes or a broken chain, the damaged part should be replaced as soon as possible.

P13 - ANOMALIES IN THE WATERPROOF LAYER

MODE: Imperfections and/or defects in the waterproofing layer and/or in the UV radiation protective layer which may affect the performance of its protective and/or insulating properties (Figure 4.37) {MD13}.

Figure 4.37. Imperfections in the protective waterproofing layer.

EFFECTS:

- **Filtration into the subsoil:** Imperfections or defects in the waterproofing layer may mean that the layer loses its properties, i.e. that it does not protect the treatment system, leading to possible wastewater leakage into the subsoil [Campbell and Ogden (1999) and Kadlec *et al.* (2000)] {E8}, and provoking a reduction of the water level in the cells {P10}.

- **Entry of water from the subsoil:** Terraforms (2002) state that the waterproofing layer prevents the entry of ground water into the constructed wetland. Therefore, if the waterproofing does not fulfil its functions and the water table is high, ground water may enter into the HSCW {E9} and as a consequence, increase the water level {P9}.

CAUSES:

- **Heavy rainfall {C5}:** Dikes constructed of compacted soil and not equipped with any other type of protection can be eroded due to the effect of the rain [Campbell and Ogden (1999), Lara and Salgot (1999) and Tousignant *et al.* (1999)].

- **Non-compliance with the characteristics of the waterproof layer {C32}:** The waterproof layer must comply with certain characteristics (i.e. resistance, thickness, etc.). Non-compliance with these characteristics may cause defects in the waterproofing capacity of the constructed wetland [Campbell and Ogden (1999), Kadlec *et al.* (2000) and Terraforms (2002)].

- **Drying of the waterproof membrane {C33}:** If the waterproofing has been made with a synthetic membrane and this membrane is not equipped with a UV radiation protector layer, or this layer is damaged, the membrane may dry out, which may lead to the waterproofing layer losing its properties [Campbell and Ogden (1999)].

- **Use of machinery {C34}:** In some HSCWs in Catalonia imperfections have occurred to the waterproofing layer as a consequence of the use of heavy machinery inside the cells and/or the incorrect use of cutting tools during the different maintenance tasks on the system.

- **Growth of trees and/or bushes around or in the HSCW area {P5}:** The growth of trees and/or bushes around or in the HSCW area may damage the waterproofing layer as a consequence of penetration by roots [Cooper *et al.* (1996), Campbell and Ogden (1999), Core Group (2000) and Terraforms (2002)].

- **Plague of rodents {P7}:** Campbell and Ogden (1999), Lara and Salgot (1999), the EPA (1999), the Core Group (2000), Crites and Tchobanoglous (2000), the Georgia Department of Natural Resources (2002) and Hygnstrom *et al.* (2002) state that rodents may damage the waterproof layer when they construct their burrows.

MONITORING: Whatever the sensitivity of the receiving media, weekly inspections are recommended in order to verify the correct state of the waterproof layer {M30}. A check of the waterproof layer is also recommended immediately after plant cutting has taken place, in addition to immediately after periods of heavy rainfall for compacted soil dikes. If any problem is detected during a visit the causes should be identified in order to apply the appropriate corrective measures:

- **Heavy rainfall {C5}:** In order to check whether the damage to the waterproof layer is a consequence of heavy rainfall, a measurement should be made of the amount of rainfall since the previous inspection of the waterproof layer {M7}. If high rainfall has been measured or is estimated this damage may be associated with the damage to the waterproof layer, and the imperfections should be rectified as detailed in the action **Restructuring the compacted soil waterproof layer {AC37}.**

- **Non-compliance with the characteristics of the waterproof layer {C32}:** In order to verify whether the problem derives from the non-compliance of the specifications of the waterproof layer, the characteristics of the waterproof layer should be checked against the recommended characteristics {M31}:

  - Synthetic membrane resistant to the weight of the gravel and resistant to solar radiation, with a thickness of between 5-10 mm.

  - Compacted soil at a level close to the waterproofing level with a thickness of 300 mm.

  If the waterproofing does not comply with the characteristics of resistance, insulation and thickness recommended, the measure **Replacing the waterproof layer {AC38}** should be carried out.

- **Drying of the waterproof membrane {C33}:** In order to verify whether the drying of the waterproof membrane is the origin of the problem, an inspection of the membrane itself is recommended {M30}. If the membrane is not protected against solar radiation, it is recommended that this protection be fitted (**Fitting a solar radiation protection layer {AC39}**). However, if the membrane is protected but the protection shows imperfections, these defects should be repaired (**Patching the solar radiation protection layer {AC40}**).

- **Use of machinery {C34}:** If the imperfections to the waterproof layer have occurred during maintenance tasks due to the use of heavy machinery or due to the inappropriate use of tools {M32}, repairing the damage through actions such as **Restructuring the compacted soil waterproof layer {AC37}, Patching the solar radiation protection layer {AC40}** and/or **Patching the waterproof membrane {AC41}** are recommended. These problems should also be taken into account the next time maintenance tasks are carried out, when considering the type of equipment and tools to be used. The advice given in the measure **Choosing the appropriate machinery {AC42}** should be followed.

- **Growth of trees and/or bushes around or in the HSCW area {P5}:** In order to verify whether the defects detected in the waterproof layer are due to the growth of trees and/or bushes the measures detailed in P5 – Growth of trees and bushes in the HSCW area and/or surrounding area are recommended, and where necessary, the actions recommended in this point. The damage caused to the waterproof layer by the actions must also be repaired, **Restructuring the compacted soil waterproof layer {AC37}** if the waterproof layer is of a compacted soil base, **Patching the solar radiation protection layer {AC40}**, if the waterproof layer is protected against solar radiation, and/or **Patching the waterproof membrane {AC41}**, if the waterproofing is a membrane.

- **Plague of rodents {P7}:** In order to verify whether the problem with the waterproof layer has been caused by rodents, the measures detailed in P7 – Plague of rodents are recommended, and where necessary the actions recommended in this point. The damage caused to the waterproof layer by the rodents' actions must also be repaired, **Restructuring the compacted soil waterproof layer {AC37}** if the waterproof layer is of a compacted soil base, **Patching the solar radiation protection layer {AC40}**, if the waterproof layer is protected against solar radiation, and/or **Patching the waterproof membrane {AC41}**, if the waterproofing is a membrane.

ACTIONS:

- **Restructuring the compacted soil waterproof layer {AC37}:** In order to repair the waterproof layer of compacted soil, (1) supply more soil and (2) compact the soil until it reaches the original levels of waterproofing.

- **Replacing the waterproof layer {AC38}:** The replacement of the waterproof layer is highly expensive as it involves removing both the vegetation of the HSCW and the matrix. If the waterproof layer is to be replaced the recommendations specified in point 4.1. Environmental problem analysis should be consulted (**Types of waterproof layer, Characteristics of the waterproof layer, and Positioning the waterproof membrane**).

- **Fitting a solar radiation protection layer {AC39}:** If the HSCW is waterproofed with a synthetic membrane and is not protected against solar radiation, fitting a layer which protects the part of the membrane exposed to the sun is recommended (Figure 4.38).

Figure 4.38. Examples of protective layers for solar radiation protection.

- **Patching the solar radiation protection layer {AC40}:** It is recommended that the solar radiation protection layer be patched using patches of the same material, correctly positioned and sealed.

- **Patching the waterproof membrane {AC41}:** It is recommended that the holes in the waterproof membrane be patched using patches of the same material, correctly positioned and sealed (Figure 4.32).

- **Choosing the appropriate machinery {AC42}:** Machinery and/or tools are necessary for plant cutting. In large systems where cutting is carried out using heavy machinery, care must be taken during the entrance and exit of the machinery into the cells. Creating zones or fitting ramps which facilitate machinery access to the cells without damaging the waterproofing, the dikes and the water distribution systems is recommended. In addition, the margins of the cells should be cut using portable grass cutting machinery which facilitates control and avoids cutting or damaging the system structures (the waterproof layer, dikes, distribution tubes, etc.). In small systems, we recommend using portable cutting machinery.

P14 - ANOMALIES IN THE DIKES

MODE: Eroded dikes, or dikes which are damaged or faulty {M14}.

EFFECTS: The main effects of damage or problems in the HSCW dikes is non-compliance with the following points: non-contention of the gravel bed and the wastewater which flows through the matrix {E10}, allowing the entrance of groundwater {E11}.

CAUSES:

- **Use of machinery {C34}:** If zones are not created for the entrance and exit of heavy machinery to and from the cells, the grass cutters used may damage the dikes.
- **Erosion of the soil {C35}:** Those dikes which are not fitted with any type of protection against erosion may suffer erosion due to the effect of the wind and rain [Campbell and Ogden (1999), Lara and Salgot (1999) and Tousignant *et al.* (1999)].
- **Growth of trees and/or bushes in the HSCW area and/or surrounding area {P5}:** Cooper *et al.* (1996), Campbell and Ogden (1999), the Core Group (2000) and Terraforms (2002) state that the roots of trees and/or bushes which grow on or around the HSCW area may damage the dikes.
- **Plague of rodents {P7}:** Campbell and Ogden (1999), Lara and Salgot (1999), the EPA (1999), the Core Group (2000), Crites and Tchobanoglous (2000), the Georgia Department of Natural Resources (2002) and Hygnstrom *et al.* (2002) state that rodents may damage the dikes when burrowing in the ground to construct their nests.

MONITORING: Tousignant *et al.* (1999) propose a weekly visit to check on the state of the dikes and to check that they have not been eroded or damaged by animals.

A daily inspection of the dikes is recommended for the HSCWs in Catalonia {M33} when the receiving media is very sensitive or sensitive, or weekly when the receiving media is resistant. Inspections are also recommended after periods of significant rainfall where the dikes are made of compacted soil. Where imperfections in the dikes have been observed, identification of the causes is recommended in order to apply the most appropriate measures:

- **Use of machinery {C34}:** In order to verify whether the damage to the dikes is a consequence of the use of heavy machinery, checks should be made to see if maintenance tasks have been carried out using this type of machinery since the last inspection {M32}. If it is confirmed that the damage has been caused by the use of machinery **Repairing the dikes {AC43}** is advised as soon as possible, taking into account the recommendations described in the action **Choosing the appropriate machinery {AC42}** in point P13 - Anomalies in the waterproof layer.

- **Erosion of the dikes {C35}:** In order to verify whether the dikes have been eroded through the action of rain or wind, it should be verified whether it has rained since the last inspection {M7} or if strong winds have affected the area {M8}. If dike erosion due to these phenomena is confirmed, repairing the damage in accordance with the recommendations in the action **Repairing the dikes {AC43}** is advised. If the wind is persistent, the action **Planting a tree screen {AC45}** as recommended in point P1 – Abnormal vegetation growth during start-up is recommended. Once the dikes have been repaired, it is recommended that vegetation be planted on the dikes as described in the action **Plant cover on the dikes {AC12}** in point P5 – Growth of trees and bushes in the HSCW area and/or surrounding area.

- **Growth of trees and/or bushes in the HSCW area or surroundings {P5}:** In order to verify whether the problems detected in the dikes are due to the growth of trees and/or bushes, the measures detailed in P5 – Growth of trees and bushes in the HSCW area and/or surrounding area are recommended, and where necessary, the actions recommended in this point. The damage to the dikes must also be repaired (**Repairing the dikes {AC43}**) as well as the action **Plant cover on the dikes {AC12}** described in point P5 – Growth of trees and bushes in the HSCW area and/or surrounding area.

- **Plague of rodents {P7}:** In order to verify whether the problems in the dikes have been caused by rodents, the measures detailed in point P7 - Plague of rodents are recommended, and where necessary the actions recommended in this point. The damage to the dikes must be repaired following the instructions described in the action **Repairing the dikes {AC43}**.

ACTIONS:

- **Repairing the dikes {AC43}:** In addition to adopting the measures related to the causes of erosion or the deterioration of the HSCW dikes, the damage must be repaired through the transportation and compacting of soil until the cell has been returned to its original condition.

Although neither significant defects nor imperfections have been detected in the dikes at the HSCWs visited in Catalonia, it is recommended that plantation of the compacted soil dikes be carried out, as this will prevent the growth of trees and bushes, plants which may damage the dikes and the waterproof layer of the HSCWs. This will also prevent the erosion of the land over time due to meteorological phenomena. The resistance of the dikes should also be taken into account when using heavy machinery for maintenance tasks.

P15 - ANOMALIES IN THE PERIMETER FENCE AND THE ACCESS GATE

MODE: The perimeter fence or the access gate show signs of damage or imperfections which hinder maintenance activities in the WWTP or allow the unhindered access of people or animals {MD15}.

EFFECTS: Inadequate maintenance of the fence and the access gate, or defects in their design may allow the entrance of people into the treatment system {E12}, with the associated risk of contact with the wastewater, and the presence of animals which may damage the plants and structural components of the HSCW {E13}.

CAUSES: The cause of the deficiencies and/or damage to the perimeter fence and the access gate may be due to poor maintenance of the system. On the other hand, the Seattle Department of Planning and Development (2000) considers that the main causes of fence-related problems are:

- **The growth of trees, bushes or weeds near the fence {C36}**
- **Plagues of rodents {P7}**

MONITORING: Weekly visits are recommended during which the state of the fence and the access gate are to be checked {M34}. If damage or defects are observed, the causes of the problem should be identified, while checking for the growth of trees, bushes or weeds close to the fence {M12}, as well as checking whether there is evidence of animals burrowing in the ground (droppings, holes, etc.) {M15}. Repairing the fence and/or gate is recommended in accordance with point: **Repairing the perimeter**

fence and the access gate {AC44}. If animals burrowing in the ground are the cause of the problem, the actions detailed in point P7 - Plague of rodents are recommended.

ACTIONS:

- **Repairing the perimeter fence and the access gate {AC44}:**
  - ◊ Where bushes, trees or weeds are growing around the fence, they should be removed up to a distance of 1 m.
  - ◊ If the poles which support the fence are out of place or in a poor state, they are to be either re-positioned or replaced where necessary.
  - ◊ If burrows and soil erosion are detected under the fence, the land will be refilled and compacted.
  - ◊ If the fence grid has holes with diameters of above 20 cm, they are to be repaired, and if necessary the fence partially or entirely replaced [Seattle Department of Planning and Development (2000)].

P16 – PRODUCTION OF BAD SMELLS

MODE: The occurrence of bad smells resulting from the natural decomposition processes of the organic material and the chemical reduction of sulphates to hydrogen sulphate. The EPA (1999) associates the production of bad smells with the creation of anaerobic conditions as a result of an organic overload or ammonia and/or an extremely large plant density {MD16}.

EFFECTS: The production of bad smells is a sign of possible problems in the WWTP, and is also a problem for operators and neighbours of the treatment plant {E14}.

CAUSES:

- **Organic overload {C1}:** The EPA (1999) associates the production of bad smells with the arrival of an influent with a high organic load.
- **Accumulation of plant debris {P3, C22 and C27}:** The plant debris which accumulates in the water distribution system {C27}, either in the area of {P3} or around the HSCW {C22} may produce bad smells when decomposing [Crites and Tchobanoglous (2000)]. On the other hand, Wood (1995) states that the accumulated plant debris, together with the plants themselves provide a kind of bio-filter which limits the emission of bad smells from the system.
- **Clogging of the substrate {P8}:** Sanford *et al.* (1995) state that one of the problems of the HSCW is the formation of bad smells resulting from the clogging of the matrix.
- **Surface flux {P9}:** According to Sanford *et al.* (1995), Blazejewski and Murat-Blasjewska (1997), the EPA (1999) and Hygnstrom *et al.* (2002) the accumulation of wastewater on the surface may produce bad smells.

MONITORING: No reference on the monitoring of bad smells has been found in the bibliography consulted. Only Hygnstrom *et al.* (2002) state that the wastewater level must be checked when there are bad smells, this is why when defining the monitoring process, the causes of the problem have been taken into account to define frequency of monitoring. In order to detect if a HSCW has a problem related to bad smells, a daily visit {M35} is recommended if the receiving media is sensitive or highly sensitive, or a weekly visit when the receiving media is resistant.

When the emission of bad smells has been detected during a visit the cause of the problem must first be identified in order to take the most appropriate actions.

- **Organic overload {C1}:** In order to verify whether the cause of bad smells is due to the treatment of an influent with organic overload, the BOD_5 of the influent {M2} should be measured as well as the water flow entering the WWTP {M3}. If during this check a BOD_5 above that of X_1 Kg $BOD_5 \cdot m^{-2} \cdot day^{-1}$ is measured, Seabloom and Hanson (2003) and Arias [Oral communication (2006)] recommend carrying out **Recirculation {AC2}.** The action **Previous treatment {AC3}** is also recommended.

- **Accumulation of plant debris {P3, C22 and C27}:** An inspection of the HSCW {M9} area is recommended, in addition to the wastewater distribution system {M28 and M29} and the surroundings of the HSCW {M36}. If the accumulation of plant debris is observed in the HSCW area the actions proposed in point P3 – Accumulation of plant debris in the HSCW area are recommended. If the accumulation of plant debris is localised in the water distribution systems, the actions **Cleaning the water distribution tubes {AC32}** and **Cleaning the water distribution channels {AC34}** should be carried out, as detailed in point P11 – Anomalies in the distribution systems and/or water collection, and finally, if the accumulation of debris is observed in the HSCW area the action **Avoiding the accumulation of debris in the HSCW area {AC19}** is recommended, as described in point P7 – Plague of rodents.

- **Clogging of the substrate {P8}:** In order to verify whether the cause of the bad smells derives from clogging in the matrix, the measures detailed in P8 – Obstruction of the matrix pores and clogging of the substrate are recommended, and where necessary the actions recommended in this point.

- **Surface flux {P9}:** In order to verify whether the production of bad smells is due to the formation of surface flux, the measures indicated in P9 – Water level too high – Formation of surface flow are recommended, and where necessary the actions recommended in this point.

P17 – HIGH CONCENTRATION OF ORGANIC MATERIAL IN THE EFFLUENT

MODE: When the BOD_5 measurement of the effluent indicates that the organic load which is being dumped is above X_3, X_4 or X_5 Kg of $BOD_5 \cdot m^{-3}$ (X_3, X_4 and X_5: limits of fixed organic load dumping depending on to whether the receiving media is very sensitive, sensitive or resistant respectively) and/or above X_6, X_7 or X_8 Kg of $COD \cdot m^{-3}$ (X_6, X_7 and X_8: limits of fixed organic load dumping depending on whether the receiving media is very sensitive, sensitive or resistant respectively) {MD17}.

EFFECTS: The dumping of this excess organic load leads to the deoxygenation of the receiving media {E15}, as well as to the contamination of the subsoil and/or aquifers {E16}.

CAUSES:

- **Organic overload {C1}:** Although one of the advantages of HSCWs is their capacity to deal with organic load shocks as a consequence of their high hydraulic retention time, the EPA (1999) states that the arrival of an influent with an organic overload may mean that desired final dumping limits are not reached.

- **Low temperatures {C2}:** The EPA (1999) states that reactions which allow the elimination of the organic matter depend on the temperature, and during the winter months these reactions may become fewer or even stop. Kadlec *et al.* (2000) also states that seasonal temperature variations may cause the performance of the HSCW to vary, and these factors must therefore be taken into account during the design phase. Karathanasis *et al*. (2003) add that the maximum performances of organic material elimination occur during the summer, and the worst occur during the winter.

- **High evapotranspiration {C4}:** According to the EPA (1988), the EPA (1999) and Kadlec *et al.* (2000), during periods of high evapotranspiration, the water retention time in the cells increases and this may cause an increase in the concentration of contaminants in the effluent.

- **Poorly developed rhizomes {C15}:** Karathanasis *et al.* (2003) attribute the deficient elimination of organic matter to an inadequately developed root system. The more mature the system, the better the elimination of organic matter.

- **Characteristics of the HSCWs {C16}:** The HSCWs themselves are generators of organic matter (plant debris and the accumulation of particles) [Lara and Salgot (1999), Kadlec *et al.* (2000) and Aguirre (2004)]. It is therefore impossible to obtain an effluent with 0 mg/l of BOD_5.

- **Depth of the cells {C23}:** According to Aguirre (2004) and García *et al.* (2004), the elimination of BOD_5 mainly depends on the organic load applied, and the depth of the cells. The shallower HSCWs have higher elimination performances (35-66%) than the deeper cells (11-40%), as the former promote the transference of oxygen and there are a greater proportion of rhizomes and roots in contact with the water.

- **Deficient growth of vegetation during the start-up {P1}:** According to the EPA (1999), the deficient growth of *Phragmites australis* means a reduction in the effectiveness of the treatment, i.e. a high concentration of organic matter in the effluent.

- **Low density or non-homogeneous density of vegetation {P2}:** The macrophytes of an HSCW intervene in the stabilisation of the substrate, the regulation of the flow; they promote the deposition of suspended solids, incorporate organic matter, nutrients and trace elements, and transfer gases between the atmosphere and the matrix [Lara and Salgot (1999)]. They also play an important role in winter as they act as an insulation against the cold [EPA (1999) and Kadlec *et al.* (2000)] and reduce the effects of the wind [EPA (1999)]. This means that a lack of plant cover or a density of plants inferior to that recommended may lead to a reduction in the efficiency of the treatment.

- **Invasion of other plants {P4}:** Invading plants which grow on the surface of an HSCW may not have the same performance as *Phragmites australis* and as a consequence they may reduce the efficiency of the treatment [Cooper *et al.* (1996)].

- **Clogging of the substrate {P8} and surface flux {P9}:** Sanford *et al*. (1995) state that if the substrate clogs and flux forms on the surface as a consequence, the water does not pass through the pores of the matrix and the water retention time is reduced. Due to this, the effectiveness of the treatment is reduced [EPA (1999) and Vymazal (2002)].

- **Water level too low {P10}:** In lowering the water level, the effective volume is reduced and therefore the hydraulic retention time is decreased. This also limits the growth and development of *Phragmites australis* [Hygnstrom *et al.* (2002), García *et al.* (2003) and Molle (Oral communication, 2004)]. Both effects mean a reduction in the efficiency of the treatment and therefore in an increase in the concentration of organic matter in the effluent.

MONITORING: When the BOD_5 {M27} and/or COD {M39} measurements made to the final effluent (weekly, fortnightly or monthly, depending on the sensitivity of the receiving media) indicate that the organic material concentration dumped is above X_3, X_4 or X_5 Kg of $BOD_5 \cdot m^{-3}$ and/or X_6, X_7 or X_8 Kg of $COD \cdot m^{-3}$, it is recommended that the cause of this problem be investigated in order to proceed with the most appropriate solution.

- **Organic overload {C1}:** In order to verify whether bad smells are caused by the treatment of an influent with an organic overload, measuring the BOD_5 of the influent {M2} is recommended, as well as the flow of water entering the WWTP {M3}. If a BOD_5 above X_1 Kg $BOD_5 \cdot m^{-2} \cdot day^{-1}$ is measured during this check, a reduction of the organic load to be treated is suggested, in accordance with the **Recirculation {AC2}** or **Previous treatment {AC3}** actions, both described in point P1 – Abnormal vegetation growth during start-up. If the HSCW is less than one year old, the action **Dilution with clean water {AC1}** may be applied, also described in point P1 – Abnormal vegetation growth during start-up.

- **Low temperatures {C2}:** In order to verify whether temperature is the cause of the increase in concentration of organic matter in the effluent, it is recommended that the temperature be measured or estimated {M4}. If local temperatures are measured or estimated to be below 6 ºC, one of the following actions is recommended: **Increasing the hydraulic retention time {AC46}, Carrying out an aerobic pre-treatment {AC47}** and **Other actions to deal with low temperatures {AC48}**.

- **High evapotranspiration {C4}:** In order to verify whether the increase in the BOD_5 or COD of the effluent is due to high evapotranspiration, this parameter should be measured {M6}. In the acquisition of data and knowledge carried out, no preventative measure has been found to solve the problem of a high BOD_5 or COD in the effluent when caused by evapotranspiration.

- **Inadequately developed root system {C15}:** If the HSCW has been operational for less than two years, it may be that the root system of the planted vegetation is not completely developed and consequently the system does not perform at full capacity. In this case, inducing the growth of the root area is recommended through the action **Promoting the development of the roots {AC16}**.

- **Depth of the cells {C23}:** In order to verify whether the applied load is appropriate, measurement of the BOD_5 in the influent {M2} and the entry flow {M3} is recommended. This data and that relating to the HSCW surface should be used to calculate the organic load applied. If this is not adequate for the depth of the cells, the load to be applied should be reconsidered in accordance with the depth of the cells. Aguirre (2004) recommends that the organic load should not be above 4 g $BOD_5 \cdot m^{-2} \cdot day^{-1}$ for HSCWs with a depth of 50-60 cm and should not exceed 6 g $BOD_5 \cdot m^{-2} \cdot day^{-1}$ for HSCWs with a depth of 30 cm. In order to adapt the load applied to the depth of the cells **Increasing the surface area of the treatment {AC49}** is recommended. This alternative requires resources which may not be available. If this action cannot be undertaken, **Promoting the transference of oxygen {AC50}** is recommended.

- **Deficient growth of vegetation during the start-up {P1}:** In order to verify whether the high concentration of organic matter in the effluent is the consequence of a deficient growth of vegetation during the initial operation of the procedure, the measures detailed in P1 – Abnormal vegetation growth during the start-up are recommended, and where necessary, the actions recommended in this point.

- **Low density or non-homogeneous density of vegetation {P2}:** In order to verify whether the high concentration of organic material in the effluent is the consequence of a low plant density and/or a non-uniform plant cover, the measures detailed in P2 – Low density or non-homogeneous density of vegetation are recommended, and where necessary, the actions recommended in this point.

- **Invasion by other plants {P4}:** In order to verify whether the high concentration of organic matter in the effluent is the consequence of the growth of weeds, the measures detailed in P4 – Growth of weeds in the HSCW are recommended, and where necessary, the actions recommended in this point.

- **Clogging of the substrate {P8}:** In order to verify whether the high concentration of organic matter in the effluent is the consequence of substrate clogging, the measures detailed in P8 – Obstruction of the matrix pores and the clogging of the substrate are recommended, and where necessary, the actions recommended in this point.

- **Surface flux {P9}:** In order to verify whether the high concentration of organic matter in the effluent is due to a formation of surface flux, the measures detailed in P9 – Water level too high – Formation of surface flow are recommended, and where necessary, the actions recommended in this point.

- **Water level too low {P10}:** In order to verify whether the high concentration of organic matter in the effluent is due to an excessively low water level, the measures detailed in P10 – Water level too low are recommended, and where necessary, the actions recommended in this point.

ACTIONS:

- **Increasing the hydraulic retention time {AC46}:** Mæhlum and Stålnacke (1999) state that one way of countering the effects of low temperatures is to increase hydraulic retention time. This counteracts low biological activity, as affirmed by the Georgia Department of Natural Resources (2002). Taylor *et al.* (1998) and Gustafson *et al.* (2001) state that hydraulic retention time must be between 10 to 13 days in order to ensure effluent quality.

- **Carrying out an aerobic pre-treatment {AC47}:** Mæhlum *et al.* (1995) and Wittgren and Mæhlum (1997) recommend carrying out an aerobic pre-treatment in winter as the reduction in temperature and the latent state of the vegetation reduces the concentration of oxygen dissolved, and limits both the elimination of organic matter as well as nitrification.

- **Other actions to deal with low temperatures {AC48}:**
  - ◊ Mæhlum *et al. (*1995) recommend not cutting the vegetation as it acts as to insulate the system.
  - ◊ Mæhlum *et al. (*1995) also propose the application of a layer of straw, some 10-15cm thick to prevent the effects of low temperatures on the HSCW performance and allows hydraulic conditions to be maintained (Figure 4.39).

Figure 4.39. Photograph of an HSCW located in Minnesota. The surface is covered with a layer of straw [Source: www.septic.coafes.umn.edu/. ../GrandLake.htm].

◊ Molle [Oral communication (2004)] suggests applying wastewater onto the ice layer as the ice will break on contact with the water at a temperature of 6-7 ºC.

♦ **Increasing the surface area of the treatment {AC49}:** Increase the surface area of the treatment by extending the existing cells, or constructing new cells which work in parallel with existing cells. The necessary extension must be proportional to the quantity of the organic load applied in excess.

♦ **Promoting the transference of oxygen {AC50}:** As mentioned previously, the elimination of organic matter in the HSCW is often limited due to a lack of oxygen. Whitney *et al.* (2003) make a series of recommendations for promoting oxygen transfer:

◊ Inducing the growth of macrophytes recommended for the HSCW (*Phragmites australis*, *Scirpus holoschoemus* and *Typha angustifolia*) as the roots of these plants have a superior penetration capacity, which improves the oxygen concentration in the matrix.

◊ Reducing the water level during the plant establishment period in order to ensure adequate penetration of the roots into the substrate.

◊ Maintaining a water level in the HSCWs which permits the formation of an air pocket above the root network.

◊ Eliminating weeds and plant debris from the HSCW surface.

P18 – HIGH CONCENTRATION OF SUSPENDED SOLIDS IN THE EFFLUENT

MODE: When the measurement of the concentration of suspended solids of the final effluent indicates that the quantity dumped is above X_9, X_{10} or X_{11} Kg of suspended solids $\cdot m^{-3}$ (X_9, X_{10} and X_{11}: limits of dumping of suspended solids established depending on whether the receiving media is very sensitive, sensitive or resistant respectively) {MD18}.

EFFECTS: The dumping of an effluent with a high concentration of suspended solids has a negative impact on the receiving media: cloudiness if the receiving media is a river, stream, natural pond, etc. {E17} or clogging if dumped onto the soil {E18}.

CAUSES:

- **High evapotranspiration {C4}:** High evapotranspiration increases the concentration of suspended solids in the effluent [EPA (1988), EPA (1999) and Kadlec *et al.* (2000)].
- **Inadequately developed root system {C15}:** Systems which are in periods of initial development do not have a sufficiently developed root system this limits the filtration process [Kadlec and Knight (1996)].
- **Characteristics of the HSCW {C16}:** The HSCWs themselves are generators of suspended solids [Lara and Salgot (1999)].
- **Deficient growth of vegetation during start-up {P1}:** According to the EPA (1999) the deficient growth of *Phragmites australis* means a reduction in the efficiency of the treatment: a high concentration of suspended solids in the effluent.
- **Low density or non-homogeneous density of vegetation {P2}:** The macrophytes of an HSCW intervene in the stabilisation of the substrate, the regulation of the flow; they promote the deposition of

suspended solids, incorporate organic matter, nutrients and trace elements, and transfer gases between the atmosphere and the matrix [Lara and Salgot (1999)]. This means that a lack of plant cover or a density of plants inferior to that recommended may lead to a reduction in the efficiency of the treatment.

- **Invasion of other plants {P4}:** Invading plants which grow on the surface of a HSCW may not offer the same performance as *Phragmites australis* and as a consequence they may reduce the efficiency of the treatment [Cooper *et al.* (1996)].
- **Clogging of the substrate {P8} and surface flux{P9}:** Kadlec and Knight (1996) and Lara and Salgot (1999) consider that the type of substrate must be taken into account, as when the substrate is clogged the hydraulic conductivity of the medium is reduced and flux forms on the surface. In these situations water does not pass through the pores of the substrate, the purification process is deficient and the concentration of suspended solids in the effluent is high.
- **Water level too low {P10}:** In lowering the water level the effective volume is reduced and therefore the hydraulic retention time is decreased. This also limits the growth and development of *Phragmites australis* [Hygnstrom *et al.* (2002), García *et al.* (2003) and Molle (Oral communication, 2004)]. Both effects mean a reduction in the efficiency of the treatment and therefore in an increase in the concentration of suspended solids in the effluent.

In Catalonia some systems have a low degree of elimination for suspended solids as they have a waste stabilization pond as a tertiary treatment phase which promotes the increase of suspended solids (algae) in the effluent.

MONITORING: When carrying out the control analysis for effluent quality {M38} (weekly, fortnightly or monthly, depending on the sensitivity of the receiving media) a concentration of suspended solids above the established limit is observed (X_9, X_{10} or X_{11} Kg of suspended solids·m^{-3}), it is recommended that the causes of this problem be identified in order to proceed with the most appropriate corrective actions.

- **High evapotranspiration {C4}:** In order to verify whether the increase of suspended solids is due to high evapotranspiration, this parameter should be measured {M6}. In the acquisition of data and knowledge carried out, no preventative measure has been found to solve the problem of a high concentration of suspended solids in the effluent when caused by evapotranspiration.
- **Inadequately developed root system {C15}:** If the HSCW has been operational for less than two years, it may be that the root system is not sufficiently well developed and the elimination of suspended solids is limited. As in the case of deficient elimination of organic material, inducing the growth of the root area is recommended through the action **Promoting the development of the roots {AC16}**.
- **Deficient growth of vegetation during the start-up {P1}:** In order to verify whether the high concentration of suspended solids in the effluent is the consequence of a deficient growth of vegetation during the initial operation of the procedure, the measures detailed in P1 – Abnormal vegetation growth during the start-up are recommended, and where necessary, the actions recommended in this point.
- **Low density or non-homogeneous density of vegetation {P2}:** In order to verify whether the high concentration of suspended solids in the effluent is the consequence of a low plant density and/or a non-uniform plant cover, the measures detailed in P2 – Low density or non-homogeneous density of vegetation are recommended, and where necessary, the actions recommended in this point.

- **Invasion by other plants {P4}:** In order to verify whether the high concentration of suspended solids in the effluent is the consequence of the growth of weeds, the measures detailed in P4 – Growth of weeds in the HSCW are recommended, and where necessary, the actions recommended in this point.
- **Clogging of the substrate {P8}:** In order to verify whether the high concentration of suspended solids in the effluent is the consequence of substrate clogging, the measures detailed P8 – Obstruction of the matrix pores and the clogging of the substrate are recommended, and where necessary, the actions recommended in this point.
- **Surface flux {P9}:** In order to verify whether the high concentration of suspended solids in the effluent is due to a formation of surface flux, the measures detailed in P9 – Water level too high – Formation of surface flow are recommended, and where necessary, the actions recommended in this point.
- **Water level too low {P10}:** In order to verify whether the high concentration of suspended solids in the effluent is due to an excessively low water level, the measures detailed in P10 – Water level too low are recommended, and where necessary, the actions recommended in this point.

b) Definition of the relationship among the 18 HSCW problems:

Characterizing the 18 problems associated with a HSCW confirms the relationship existing between them. As introduced in point 4.2.2.2. Categorization, this relationship can be defined at various levels:

b1) Problem – Cause: 12 of the 18 problems identified can cause other problems (Figure 4.40):

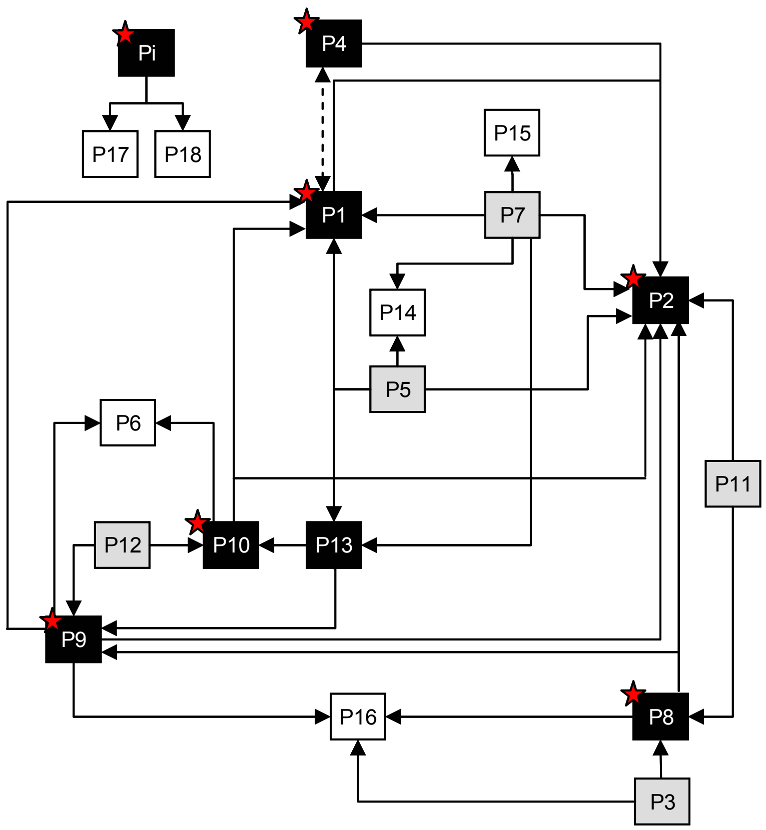

Figure 4.40. Relationship existing between problems.
The P_i marked with a red star are also causes of problems P17 and P18.

- 7 problems ({P1}, {P2}, {P4}, {P8}, {P9}, {P10} and {P13}, marked with a black box and white letters in Figure 4.40) can be caused by another problem. At the same time, they can be a causal factor for a dysfunction. The relationship between two of the problems included in this group ({P1} and {P4}, marked with a double discontinuous arrow in Figure 4.40), forms a unique curve, so while {P1} (Deficient growth of vegetation during system start-up) can favour the appearance of {P4} (Invasion of weeds), {P4} can cause {P1}.

- 5 problems ({P3}, {P5}, {P7}, {P11} and {P12}, marked by a grey box with black letters in Figure 4.40) can cause other problems, but among the causes behind them there are no problems.

b2) Problem – Effect: 13 of the 18 problems identified might originate from other problems. As has been stated in the previous paragraph, the problems {P1}, {P2}, {P4}, {P8}, {P9}, {P10} and {P13} (marked with a black box and white letters in Figure 4.40) can cause as well as be caused by problems. The problems {P6}, {P14}, {P15}, {P16}, {P17} and {P18} (marked with a white box and black letters in Figure 4.40 are not the cause of other problems, while among the causes behind them there are other problems.

b3) Problem – Action: Applying one of the actions to avoid the growth of weeds in the a HSCW {AC10} (Light flooding of the HSCW) represents the appearance of the problem {P9} (Water level too high – Surface flow formation), as well as favouring the appearance of problems {P1}, {P6}, {P16}, {P17} and {P18} related with {P9} (Figure 4.41).

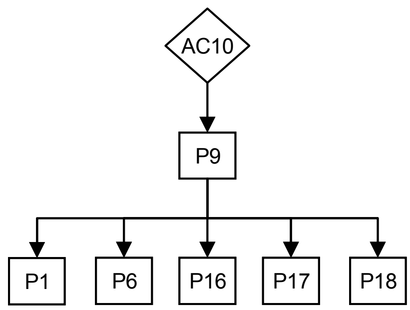

Figure 4.41. Relationship between action {AC10} and problem {P9}.

b4) Effect – Cause: The problems {P5}, {P7}, {P8} and {P11} have a common effect: {E1} (Poor distribution of the water entering the pools). The appearance of this effect can make the establishment of plant cover difficult and favour the appearance of problem {P2} (Figure 4.42).

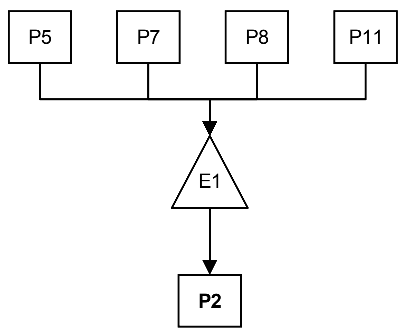

Figure 4.42. Relationship between effect {E1} and the problem {P2}.

c) Minimum frequency of the measures:

As stated, the minimum frequency recommended with which the measures to detect the problems associated with a HSCW have to be carried out is set according to:

- The characteristics of the problem, especially (1) the dynamic, (2) the frequency with which it becomes apparent, (3) the social impact and (4) the environmental impact of the same.

- The sensitivity of the receiving environment.

c1) Dynamic of the problem: According to the dynamic we find 3 types of problems:

- **Slow dynamic problems:** Within the slow dynamic problems we find those problems that become apparent gradually:
  - Vegetation: Set of problems related with the vegetation from the HSCW and/or from the surrounding area: {P1}, {P2}, {P3}, {P4}, {P5} and {P6}. These are slow dynamic problems due to the growth rate of the plants, as well as of the appearance of disease (P6 - Chlorosis); they do not become apparent from one day to the next.
  - Matrix: Problem related with the total or partial clogging of the matrix {P8}. This problem has a relatively slow dynamic depending on its cause: if it is biological (e.g. growth of micro-organisms {C24} or accumulation of plant remains {P3}), it will be slower than in the opposite case (e.g. the matrix diameter is too small {C21}).
  - Bad odours: Problem related with the formation of bad odours {P16}. This problem has a slow dynamic because the causes behind it appear gradually.
  - Effluent quality: Set of problems regarding the concentration of organic matter {P17} and of suspended solids {P18} in the effluent. These problems have a relatively slow dynamic due to the high hydraulic residence time and to the capacity of the HSCW to confront load shocks.
- **Fast dynamic problems:** Set of problems that become apparent suddenly, even in a matter of hours:
  - Rodents: Problem related with the proliferation of rodents {P7}. This problem can appear suddenly, so from one day to the next we might find rodents in the WWTP.
  - Water regime: Set of problems related with the distribution of water through the cells {P9}, {P10}, {P11} and {P12}. These problems are characterised by a relatively fast dynamic, especially when they are not due to the accumulation of solids.
- **Variable dynamic problems:** Set of problems whose dynamic varies considerably according to their causes, from a few hours to even months:
  - Structures: Set of problems related with different structural parts of the HSCW: waterproof layer {P13}, dikes {P14} and perimeter fence and access gate {P15}. The dynamic of these problems varies according to their causes, so they can appear from one day to the next when the causes are precipitations {C5}, the use of machinery {C34} or rodents {P7}, while they will become apparent gradually for the other reasons (e.g. the growth of trees and/or bushes {P5}).

c2) Frequency with which the problem becomes apparent, social impact and environmental impact: These factors, to be taken into account when establishing the minimum frequency with which the measures have to be carried out, are summarised in Figure 4.43. The 18 identified problems are located in the 3D graphic depending on the frequency with which they appear and their social and environmental impacts. It can be inferred from this that problem {P9}, related with surface flow formation, is the most important in an HSCW because (1) it occurs often and it has a high (2) social impact and (3) a high environmental impact. It should also be pointed out that while 90% of the problems have an important environmental impact, only 25% have a high social impact.

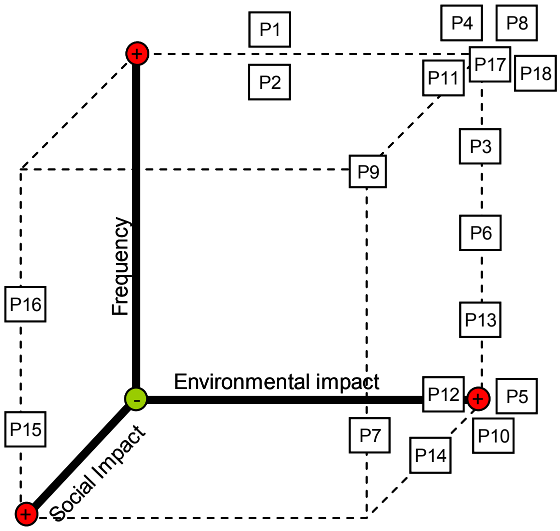

Figure 4.43. Representation of the problems associated with an HSCW according to the frequency with which they appear and their social impact and environmental impacts.

c3) Sensitivity of the receiving media: The degree of sensitivity of the receiving media is defined based on its capacity to absorb contaminants and the usefulness of that. As has been stated, the data and knowledge of the receiving media are extracted from the EDSS knowledge base of the PSARU-2002. Therefore, taking into account the available information, the capacity of the receiving media to absorb contaminants is defined according to:

- Months of the year that the receiving media has water.
- The nitrate vulnerability of the receiving media.
- Classification as a PEIN area (*Pla d'Espais d'Interès Natural* / Plan for Areas of Natural interest).

For the usefulness of the receiving media the following is taken into account:

- The existence of wells and/or aquifers from which water can be extracted.
- The existence of swimming and/or fishing areas.

Using these parameters, the receiving media is classified as very sensitive, sensitive or resistant.

Based on the five factors defined (dynamic, frequency of the problem, social impact, environmental impact and sensitivity of the receiving media), the minimum frequencies with which the measures have to be carried out in order to identify the problems (Table 4.6) are set. As can be seen, the minimum visit frequency to an HSCW is once a week. The frequency increases up to once a day, in order to monitor some problems with a high environmental impact and/or with a high social impact located in areas where the receiving media is classified as very sensitive or sensitive. For some problems, the frequency varies depending on the season of the year. For the rest, whatever the sensitivity of the receiving media is, the control frequency is maintained.

Table 4.6. Minimum frequencies recommended for the measures proposed to detect problems.

Problem	Dynamic	Problem frequency	Environmental impact	Social impact	Control frequency*[1]		
					VS	S	R
P1	Slow	High	Medium	Low	T	T	W
P2	Slow	High	Medium	Low	W	W	W
P3	Slow	High	High	Low	W	W	W
P4	Slow	High	High	Low	W*[2]	W*[2]	W*[2]
P5	Very slow	Low	High	Low	M	M	M
P6	Slow	Medium	High	Low	W	W	W
P7	Fast	Low	High	High	D	D	W
P8	Quite slow	High	High	Low	D	D	W
P9	Quite fast	High	High	High	D	D	W
P10	Quite fast	Low	High	Low	D	D	W
P11	Quite fast	High	High	Low	D	D	W
P12	Quite fast	Low	High	Low	D	D	W
P13	Variable	Low	High	Low	W	W	W
P14	Variable	Low	High	Medium	D	D	W
P15	Variable	Low	Low	High	W	W	W
P16	Slow	Medium	Low	High	D	D	W
P17	Quite slow	High	High	Low	W	F	M
P18	Quite slow	High	High	Low	W	F	M

*[1] VS: Very sensitive; S: Sensitive; R: Resistant; D: Daily; T: Two or three times a week; W: Weekly, F: Fortnightly; M: monthly.
*[2] Weekly in springtime, fortnightly in summer and autumn, monthly in winter.

- **Vegetation:** Although the problems of vegetation ({P1}, {P2}, {P3}, {P4}, {P5} and {P6}) have a high environmental impact, their slow dynamic means that a weekly measure is adequate.

  For problem {P1}, and when the receiving media is very sensitive or sensitive, it is recommended to increase the control frequency to two or three times per week given (1) the fragility of the plants during the implementation of the system, and (2) the importance of obtaining a dense and vigorous plant cover from the very beginning.

  In the case of problem {P4} the option of diminishing the frequency of visits during the summer, the autumn and the winter is given because in these seasons of the year the growth velocity of weeds diminishes as a result of meteorological conditions.

  For problem {P5} a monthly control is sufficient because the tree growth is slow.

- **Rodents:** The problem of rodent proliferation {P7} occurs with little frequency in the HSCW of Catalonia, but because this is a problem with a fast dynamic and high environmental and social impacts, it is recommended to implement a daily measure when the receiving media is very sensitive or sensitive, and a weekly one when the receiving environment is resistant.

- **Matrix:** The clogging of the matrix {P8} is a problem with a relatively slow dynamic, but it is recommended to control it on a daily basis when the receiving environment is very sensitive or sensitive because it occurs often and has a high environmental impact.

- **Water regime:** The problems encompassed in this group ({P9}, {P10}, {P11} and {P12}) are characterised by having a fast dynamic and a high environmental impact, and in addition, some of them

({P9} and {P11}) appear often, and for these reasons it is recommended to control it on a daily basis when the receiving media is very sensitive or sensitive, and weekly when the receiving media is resistant.

- **Structures:** In this set we find the variable dynamic problems. Problem {P13} has a high environmental impact but is it occurs infrequently and has a low social impact. For this problem weekly control is recommended. Problem {P14} also occurs infrequently, but in addition to a high environmental impact it has considerable social impact. Therefore, for this problem daily control is recommended when the receiving media is very sensitive or sensitive, and weekly when the receiving media is resistant. Finally, for problem {P15} weekly control is proposed because, even though it has a high social impact, it appears infrequently and has a low environmental impact.
- **Bad smells:** The problem of bad smells {P16}, although having a slow dynamic, is presented with a certain frequency. This problem has a high social impact, and even though it is considered to have a low environmental impact, it is an indication that the HSCW does not work correctly, which can be due to problems that do have environmental impacts. For these reasons daily control is recommended when the receiving media is very sensitive or sensitive, and weekly when it is resistant.
- **Quality of the effluent:** The two problems grouped together in this set ({P17} and {P18}), despite having a relatively slow dynamic, appear frequently and have a high and important environmental impact. Nevertheless, the economic cost of these controls means that weekly control is recommended when the receiving media is very sensitive, fortnightly when the receiving media is sensitive and monthly when it is resistant.

d) Reasoning process to define the operational and maintenance protocols based on the defined categories:

The analysis of the acquired data and knowledge also led to the establishment of a reasoning process to define operation and maintenance protocols according to the categories identified (Figure 4.44). The causes behind the disturbances are the starting point of this reasoning process. These factors are identified among the characteristics of the community, the WWTP configuration and the HSCW design. From the causes it is possible to preview the potential disturbances as well as to define the preventive actions aiming at keeping the causes from occurring. Continuous or repeated observations or measures to determine the level of compliance with performance requirements and pollutant levels (monitoring tasks) are needed. These controls are defined by considering problems and causes together since it is important to both: (1) detect the problem and (2) identify the cause of the disturbance. The problem-cause combination is also considered in the definition of corrective actions. Since a particular problem can result from different causes, it can be solved by applying different actions. Once a problem appears, the kinds of effects depend on the characteristics of the community, the WWTP and the receiving environment. Also, the intensity of these effects varies depending on the sensitivity of the receiving environment. Consequently, it is proposed to define the frequency of the measures and preventive actions in accordance with this sensitivity, i.e. the more sensitive the receiving media is, the more frequently controls and preventive actions will be needed. All this information related to problems, causes, measures, preventive and corrective actions, and effects will be included within the operation and maintenance protocols provided by EDSS-maintenance.

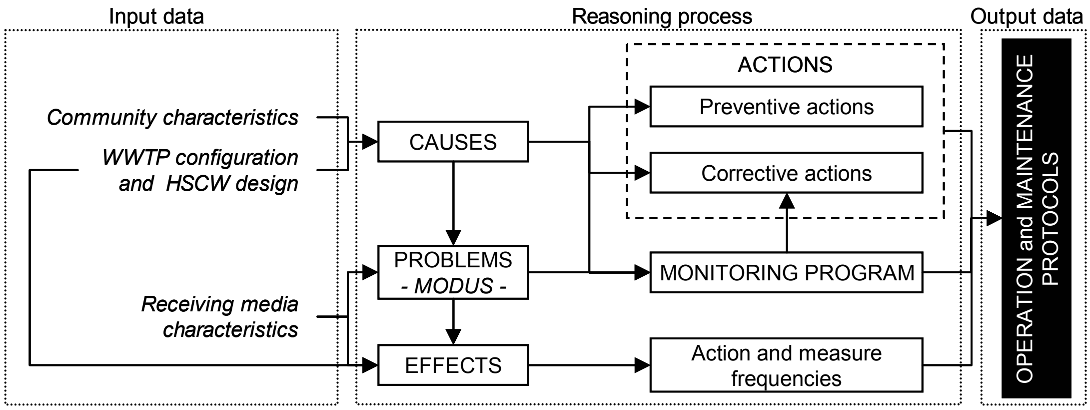

Figure 4.44. Reasoning procedure proposed to obtain the operation and maintenance protocols.

4.2.3. Recommendations to build the full EDSS-maintenance

The data and knowledge acquisition to develop the full EDSS-maintenance will be focused on the identification and characterization of problems associated with the other technologies involved in the PSARU 2002 project (Table 4.1). To perform this study we recommend improving the methodology used in the acquisition of HSCW information in the following aspects:

- Distributing the questionnaires to other Mediterranean regions in which the technologies recommended in the PSARU 2002 project to treat wastewater of small communities are used (i.e. Andalusia, Valencia or South of France).
- Improving the quantity and quality of knowledge extracted from the interviews through of field studies focused on the monitoring program and the operational and maintenance tasks performed.

The main objective of these proposals is to confront the lack of technical knowledge about operation and maintenance observed for some of these technologies.

Since the high-loaded technologies (i.e. extended aeration, sequencing batch reactors and rotating biological contactors) are more monitored than the low-loaded ones, it is expected that more data will be available. Hence, although the categorization process allowed the identification and characterization of each problem (both as a single entity and as a part of a set of problems) we propose to consider the type and the quantity of information and then decide which analysis process is better: KDD, categorization or a combination of both processes.

The reasoning procedure proposed to define operation and maintenance protocols for HSCWs will be reused to develop the full EDSS-maintenance hence, whatever the data and knowledge analysis process performed, this procedure must permit the identification and characterization of problems as a single entity in terms of (Figure 4.45):

- Modes or definition of the problem.
- Causes behind a problem.
- Effects of the problem on the environment.
- Measures to identify the problems and the causes that unleash this dysfunction.
- Actions applied to prevent or eliminate the causes that unleash the problem.

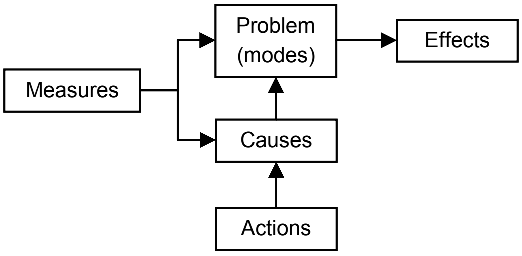

Figure 4.45. Characterization of a problem.

Moreover, allowed the relations existing among problems to be defined: a problem can be the origin of another problem (Figure 4.46, a); an effect of a given problem can cause other disturbances (Figure 4.46, b); the application of a corrective action can unleash a problem (Figure 4.46, c); etc.

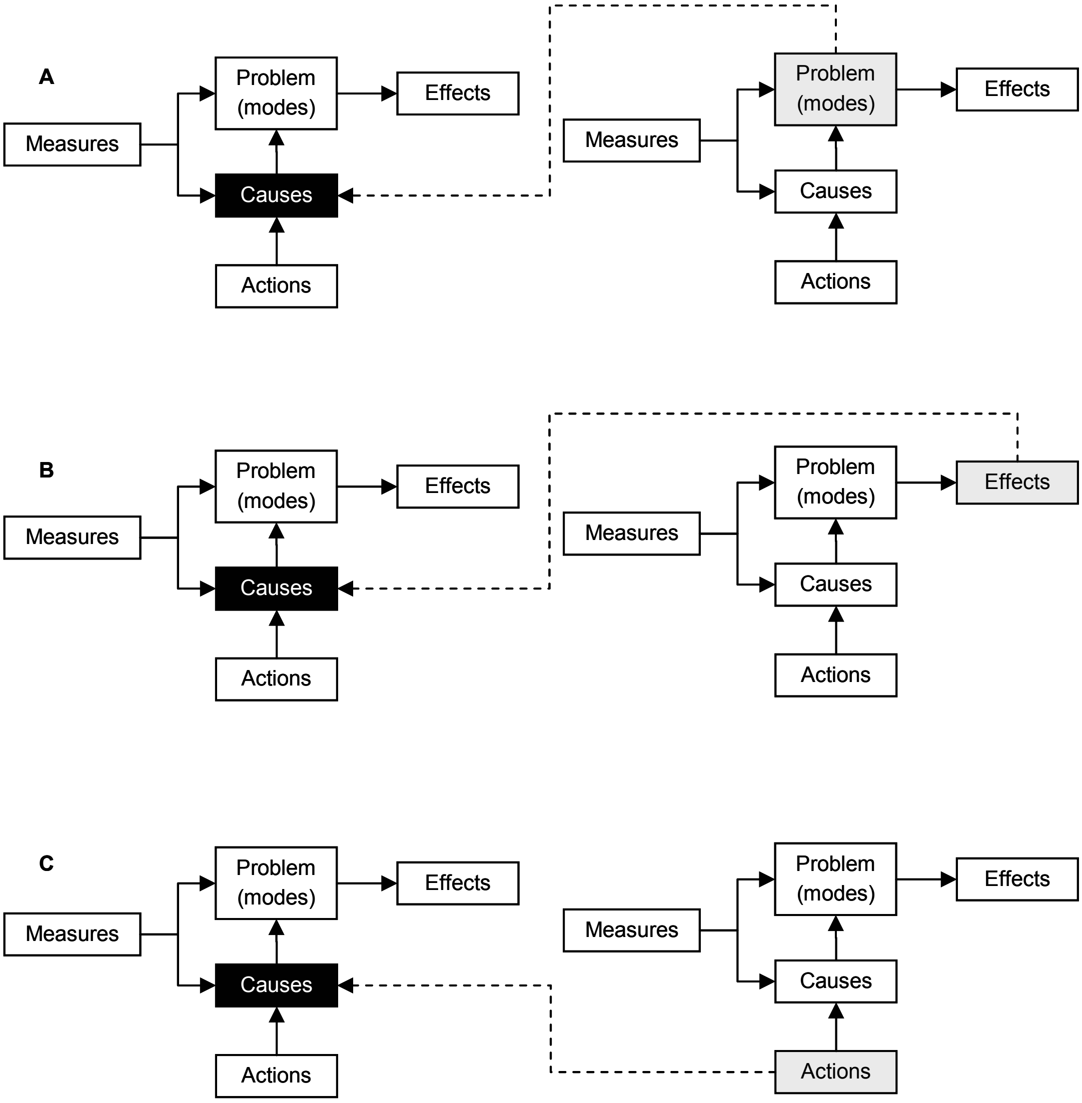

Figure 4.46. Possible relationships among problems: (A) a problem causes a problem, (B) an effect causes a problem and (C) an action causes a problem.

4.3. Model selection

The third step in the development of an EDSS consists in the selection of models to represent the data and knowledge acquired in the second step. This selection must take into account the following aspects [Turon *et al.* (2006, b)]:

a) The aim of the EDSS (i.e. diagnosis, planning, prediction, design, *etc.*).

b) The processes involved within the environmental problem.

c) The type of knowledge available: quantitative and/or qualitative data.

d) The amount of data and knowledge available.

Hence, before selection of the model (4.3.2. Justification of the model selected) all these aspects were evaluated (4.3.1. Considerations for the model selection). Once the set of models was selected, this stage was completed by choosing the most adequate platform in terms of license cost and software potential (4.3.4. Software selection).

4.3.1. Considerations for the model selection

The aim of EDSS-maintenance is to provide support for the definition of operation and maintenance protocols. At first sight the EDSS-maintenance prototype can therefore be considered a planning tool because it aims to provide plans for the correct functioning of HSCWs.

However, the EDSS-maintenance objective can be broadened to other levels; an in-depth study of processes involved in the definition of operation and maintenance protocols led to the definition of two types of plan: (1) diagnosis plans and (2) therapy plans. A second approach to the processes permitted the identification of different aims in both types of plan. While diagnosis plans are based on the definition of a monitoring program to identify problems and their causes, therapy plans are focused on the definition of preventive actions (to avoid problems) and corrective actions (to solve problems). This second approach also allowed the identification of another aim of the operation and maintenance protocols: specifying the effects problems have on the environment, i.e. the prediction of consequences of problems.

Another relevant aspect was extracted from the second in-depth study: the processes involved in defining the operation and maintenance protocols are similar to the human reasoning process.

The data and knowledge required to solve the environmental problem was extracted from the literature, and was then updated and validated by HSCW experts. As a consequence, expert knowledge is the predominant available information. Furthermore, the information acquired is not too voluminous (around 250 objects) and can be easily understood and digested.

EDSS-maintenance was planned as an offline tool: from offline input data (characteristics of the community, the WWTP and the receiving media) it provides offline output data (operation and maintenance protocols).

4.3.2. Justification of the model selected

Among the numerical, statistical and AI models, the rule-based model was selected as an appropriate model to represent the data and knowledge required to define the protocols for HSCWs.

Numerical and statistical models were discarded as expert knowledge cannot be represented by means of mathematical expressions or statistical parameters.

The rule-based model was selected from the AI models because:

- The main objective of EDSS-maintenance prototype is defining plans to guarantee the correct functioning of HSCWs. These plans have three sub-objectives: (1) the diagnosis of problems, (2) the prevention and solution of problems, (3) the prediction of effects on the environment. According to Turban (1992), Krishnamoorthy and Rajeev (1996), diagnosis, monitoring, therapy proposal and prediction can be addressed efficiently using RBSs.
- The data and knowledge required to define operation and maintenance protocols is mainly expert knowledge and RBSs are ideal for tasks involving reasoning based on heuristics and qualitative knowledge [Krishnamoorthy and Rajeev (1996)].
- Other EDSSs developed using the methodology proposed by Poch *et al.* (2004) have employed RBSs to represent data and knowledge (3.6. Justification of the methodology selected).
- RBSs were developed by AI researchers during the 1960s [Rolston (1991) and Turban (1992)]. Since then they have been applied in diverse fields, although the potential use of RBSs in the field of wastewater was not introduced until 1980s, and for different purposes:
  - WWTP planning [Okubo *et al.* (1994), Chin-Tien and Jehng-Jung (1996), Comas *et al.* (2003, a) and Adenso-Diaz *et al.* (2005)].
  - WWTP design [Geselbracht *et al.* (1986), Hudson *et al.* (1997), Sairan *et al.* (2005) and Comas *et al.* (2006)].
  - WWTP diagnoses [Lapointe *et al.* (1989), Bergh and Olsson (1996), Puñal *et al.* (2000) and Pires *et al.* (2005)].
  - WWTP operation and control [Ladiges and Kayser (1993), Serra *et al.* (1993), Ozgur and Stenstrom (1994), Zhu and Simpson (1996), Baeza *et al.* (2000), Flores *et al.* (2000), Baeza *et al.* (2002), Rodríguez-Roda *et al.* (2002), Comas *et al.* (2003, b), Martinez (2006), Rodríguez-Roda *et al.* (2006 and Xu *et al.* (2006)].

  All these references allow verification of the applicability of RBS in representing the data and knowledge required to solve environmental problems within the field of wastewater.

4.3.3. Rule-based system

RBSs are relatively simple computer programs designed to imitate the reasoning process and knowledge of experts in solving problems in a particular domain. The program uses the domain knowledge coded by means of IF-THEN rules and a specified control strategy to arrive at solutions [Turban (1992) and Krishnamoorthy and Rajeev (1996)].

RBSs are composed of two major parts [Rolston (1991), Turban (1992) and Krishnamoorthy and Rajeev (1996)] (Figure 4.47):

- **Knowledge base:** The knowledge base contains the necessary knowledge for understanding, formulating and solving problems. It includes two basic elements:
  - ***Facts:*** A statement or assertion of verified information about something that represents the initial working memory.
  - ***Rules:*** The rules should encompass all actions to be taken within the scope of a problem but nothing irrelevant.

- **Inference engine:** The brain of the RBS is the inference engine. This component is essentially a computer program that provides a methodology (1) for reasoning about information in the knowledge base and in the blackboard (area of working memory set aside for the description of the current problem), and (2) for formulating conclusions.

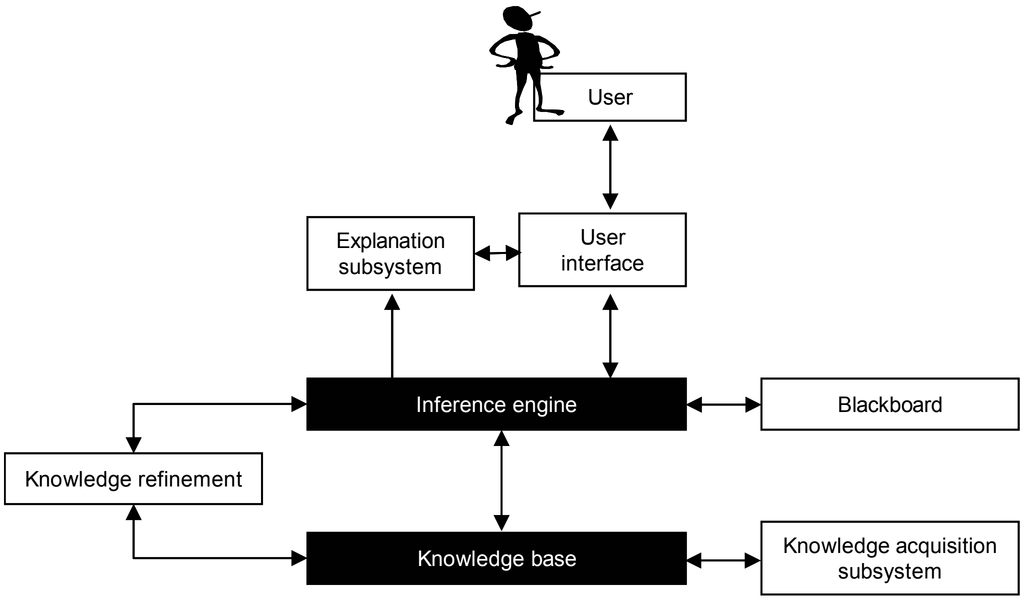

Figure 4.47. RBS architecture [modified from Rolston (1991) and Turban (1992)].

Moreover, the following components may exist in an RBS [Rolston (1991) and Turban (1992)] (Figure 4.47):

- **Knowledge acquisition subsystem:** Knowledge acquisition is the accumulation, transfer and transformation of problem-solving expertise from some knowledge source (i.e. databases, textbooks, human experts, etc.) to a computer program for constructing or expanding the knowledge base.

- **Blackboard or workplace:** The blackboard is an area of working memory set aside for the description of a current problem (as specified by the input data). It is also used for recording intermediate results.

- **User interface:** RBSs contain a language processor for friendly, problem-oriented communication between the user and the computer. This communication is usually carried out in a natural language, but in some cases it is supplemented by menus and graphics.

- **Explanation subsystem or justifier:** The ability to trace responsibility for conclusions to their sources is crucial both in the transfer of expertise and in problem solving. The explanations subsystem can trace such responsibility and explain RBS behaviour (i.e. How was a certain conclusion reached? Why was a certain alternative rejected? What is the plan to reach the solution?).

- **Knowledge refining system:** RBSs must be evaluated in order to analyze their success or failure. This could lead to improvements that result in a better knowledge base and more effective reasoning. These modifications are usually made manually by the RBS developer or the RBS user.

The RBS mechanism is based on the comparison of (1) data (input data and intermediate results) stored in the working memory and (2) the IF condition part of rules stored in the knowledge base. The inference engine allows the triggering of those rules whose conditions are satisfied. When a rule is fired, any actions specified in its THEN clause are carried out. These actions can provide an intermediate result which can trigger another rule or apply for more input data from the user. This loop of firing rules and performing actions continues until one of these two conditions is met: (1) there are no more rules whose conditions are satisfied or (2) a rule is fired whose action specifies the program should terminate.

4.3.4. Software selection

Choosing which software tool to use is an important decision in the development process. The choice depends on several factors such as: (a) the license cost, (b) the ease of encoding and (c) its potentialities. In this respect, the aspects considered in the selection of the EDSS-maintenance software were:

- The budget to build software was limited.
- The software had to allow the easy codification of knowledge by means of IF-THEN rules.
- The number of rules was not very large.

With these constraints in mind, we looked for free or low cost software that allowed the easy representation of knowledge by means of heuristic rules. The low number of rules to be codified made this search easy because free or low-cost software is not usually recommended for codifying a large number of rules.

In a first approach, Java (Sun Microsystems) and Jess (Sandia National Laboratories) software programs were selected:

- Java [http://www.java.com] is a high-level, object-oriented programming language developed initially by James Gosling and colleagues at Sun Microsystems. It is similar to C++, but has been simplified to eliminate language features that cause common programming errors. Java is a general purpose programming language with a number of features that make the language well suited for use on the Web. Small Java applications are called Java applets and can be free downloaded from a Web server and run by a Java-compatible Web browser such as Netscape Navigator or Microsoft Internet Explorer.

- Jess [http://www.jessrules.com] is a rule engine and scripting environment written entirely in Sun's Java language by Ernest Friedman-Hill at Sandia National Laboratories. Using Jess, it is possible to build Java software that has the capacity to "reason" using knowledge supplied in the form of declarative rules.

Jess is small, light, and one of the fastest rule engines available. Jess is available at no cost for academic use worldwide, but commercial users have to purchase a Jess license.

These two software programs allowed the development of a first version of the EDSS-maintenance prototype. Although this system worked perfectly, economic restrictions lead to the Jess software being substituted for Drools. Drools is also much easier to integrate with Java software:

- Drools [http://drools.org] is an objected-oriented rule engine for Java. It is an augmented implementation of Forgy's Rete algorithm tailored for the Java language. Adapting Rete to an object-oriented interface allows for more natural expression of rules with regard to objects. More importantly, Drools provides for declarative logic programming and is flexible enough to match the semantics of the problem domain. The various parts that compose a rule may be extended to lend domain-specific sense to the rule. Moreover, Drools software can be downloaded free from the network.

4.3.5. Recommendations to build the full EDSS-maintenance

Although RBSs have been widely used in the development of EDSSs in the wastewater framework, some researchers around the world do not recommend using RBSs mainly because this AI methodology does not have learning capabilities and the revision and upgrading of rules is complicated (mainly when there is a huge number of rules and these rules are not well organized).

EDSS-maintenance prototype does not require a huge number of rules, but given that we do not know the quantity and quality of data and knowledge that will be obtained for the other wastewater treatment technologies involved in the PSARU 2002 project, we propose repeating the procedure to select the model in each technology (4.3.1. Considerations for the model selection and 4.3.2. Justification of the model selected) and to choose the most appropriate model according to the type of information available (i.e. if numerical data is available then we can select a numerical model, if specific knowledge is predominant then we can use CBS, *etc*.).

Java and Drools software programs (both software are free) have been selected to develop the EDSS-maintenance prototype. The combination of these two software tools allows a much easier codification of the HSCW information and representation of the processed information by means of user-friendly interfaces. But, whenever the knowledge will be represented using another model (CBS, neural networks, lineal models, etc.) we recommend carrying out a review of the available software to select the most appropriate tool.

4.4. Model implementation and integration

Once the knowledge acquisition process was completed and the model selected, the acquired information was transformed into a graphical representation which was easy for experts to understand and amend. The entire knowledge base was organized into 37 decision trees and one matrix (4.4.1. Knowledge representation). This knowledge was then converted into IF-THEN rules (4.4.2. Knowledge codification). Since the development of EDSS-maintenance involved only one model (RBS), no integration was required.

4.4.1. Knowledge representation

Although the acquired data and knowledge was represented in decision tree form, it is possible to distinguish three kinds of diagrams:

1) Knowledge about modes, causes, monitoring programs and actions was organized into eighteen decision trees (Figure 4.48 – 4.65). These diagrams permit the identification of problems and their causes. These decision trees also allow definition of the most appropriate corrective actions (4.4.1.1.Modes, cause, monitoring program and action decision trees).

2) Knowledge about effects was organized into eighteen simple decision trees (Figure 4.66 – 4.83). These graphs allow the consequences of problems to be identified (4.4.1.2. Effect decision trees).

3) Knowledge about the receiving media was organized and documented in a decision tree (Figure 4.84). This diagram allows the sensitivity of the receiving environment to be categorized as very sensitive, sensitive or resistant (4.4.1.3. Receiving media decision tree).

These decision trees are presented on the following pages. Furthermore, in order to facilitate comprehension of this knowledge representation, there is a definition of the codes used in these diagrams in Annex II – Glossary.

All knowledge recommending the frequency of measures required to identify the problems was structured into one matrix (4.4.1.4. Frequency matrix). This matrix also includes the action {AC56} – Cut the macrophytes. Despite the fact that this action can be applied as a preventive or a corrective action, whatever the characteristics of the HSCWs, {AC56} was defined as preventive action in the protocols. For this reason this action does not appear in the decision trees shown in point 4.4.1.1. Modes, cause, monitoring program and decision trees, but only appears in the matrix of frequencies (4.4.1.4. Frequency matrix).

4.4.1.1. Modes, cause, monitoring program and action decision trees

The first step in the modes, cause, monitoring program and action decision trees (Figure 4.48 – 4.65) is evaluation of the characteristics of the HSCW ( ) in order to identify which of the eighteen problems can appear ( ). When faced by a potential problem, the modes ( ) and the measure ( ) to identify it are provided. The list of causes (and) and the measures to identify these causes ( ) are then supplied. Finally, corrective actions are provided ( ). While some of these corrective actions are recommended for a given cause, others can be applied to a group of causes (actions located below the bracket - - can be applied to causes above it). Some causes and actions depend on the characteristics of the HSCW. In these cases, prior to definition of these terms an evaluation of the characteristics of the HSCW is required ( ).

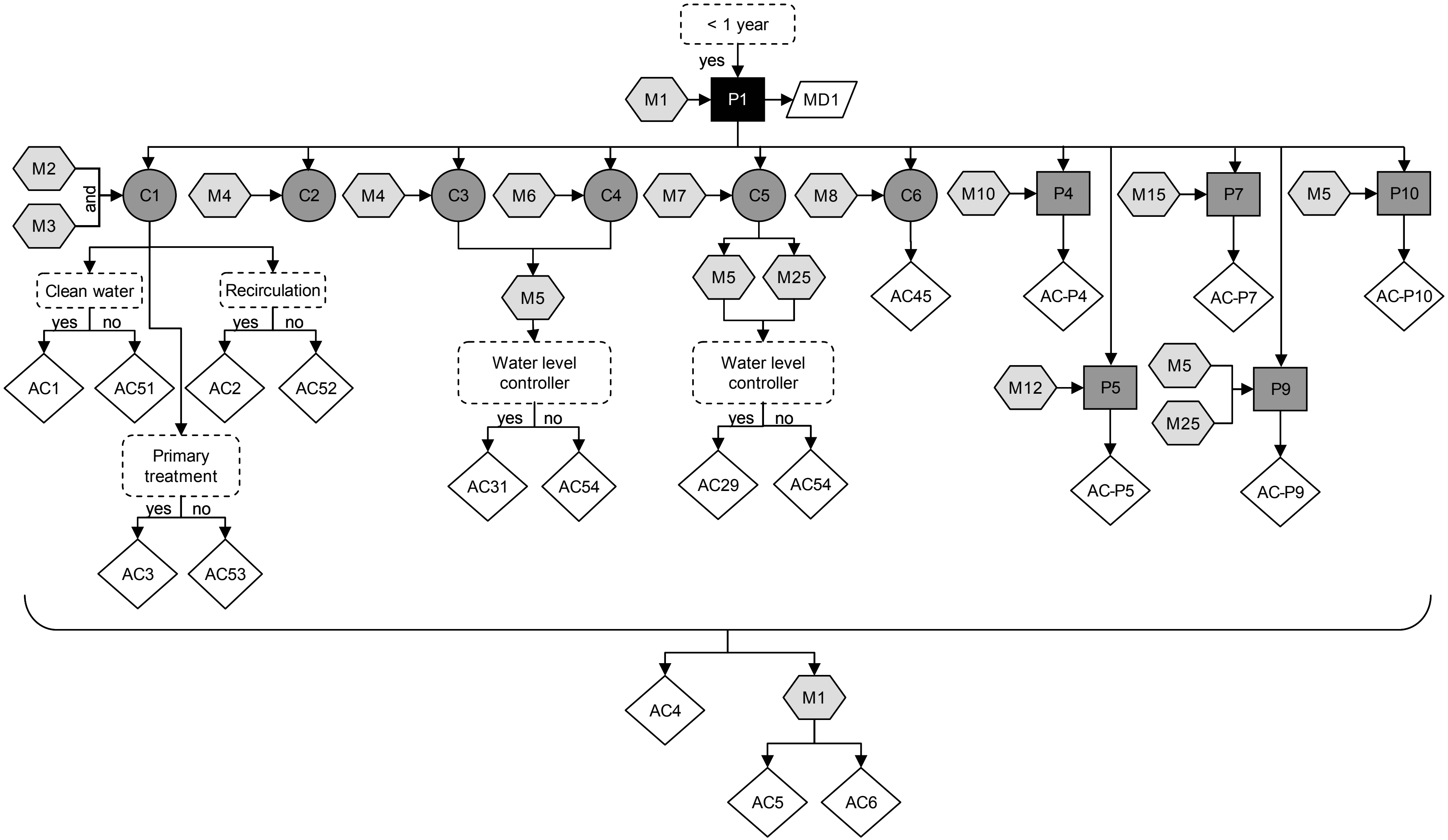

Figure 4.48. Decision tree for the diagnosis and solution of deficient vegetation growth during the start-up {P1}.

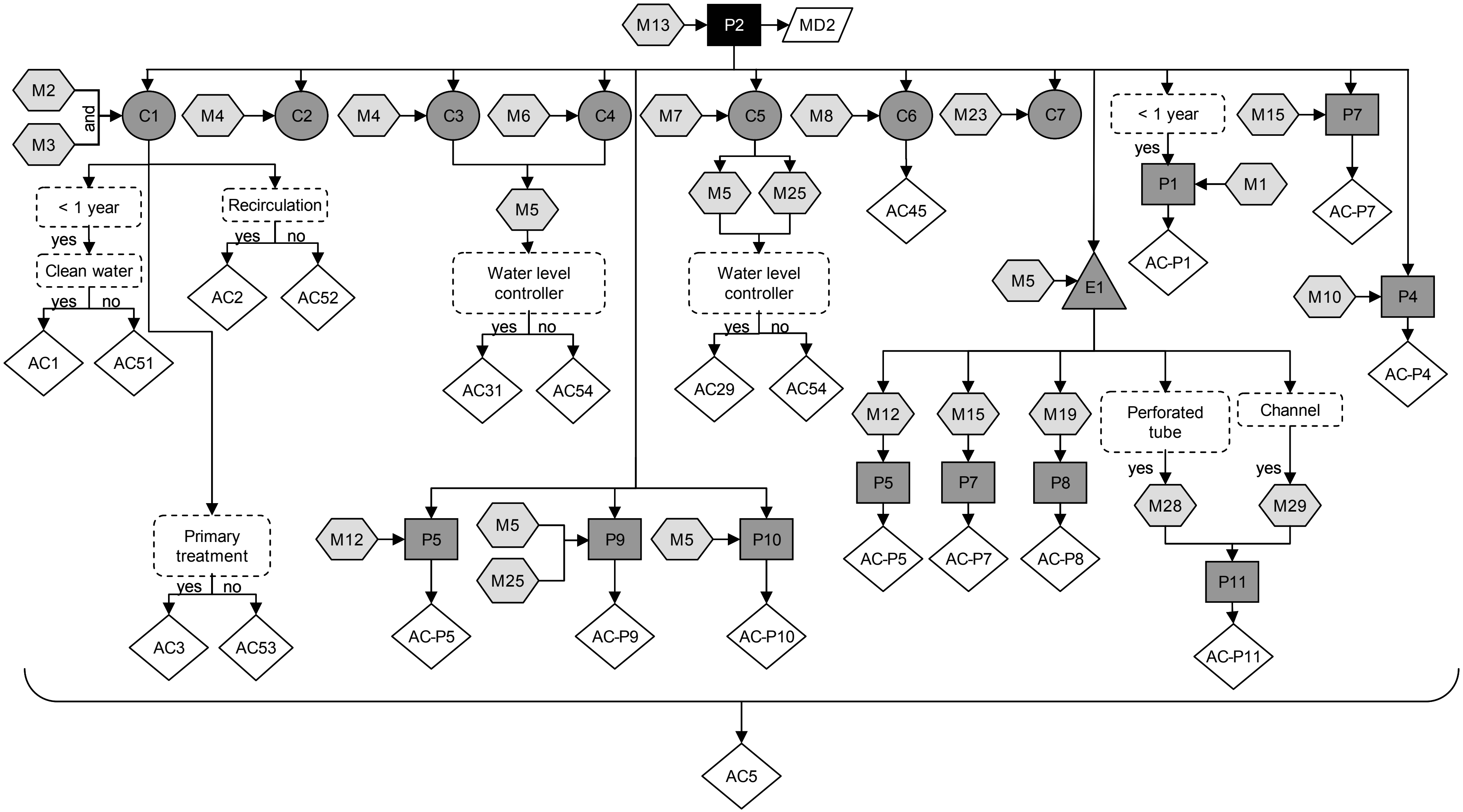

Figure 4.49. Decision tree for the diagnosis and solution of low density or heterogeneous growing of *Phragmites australis* {P2}.

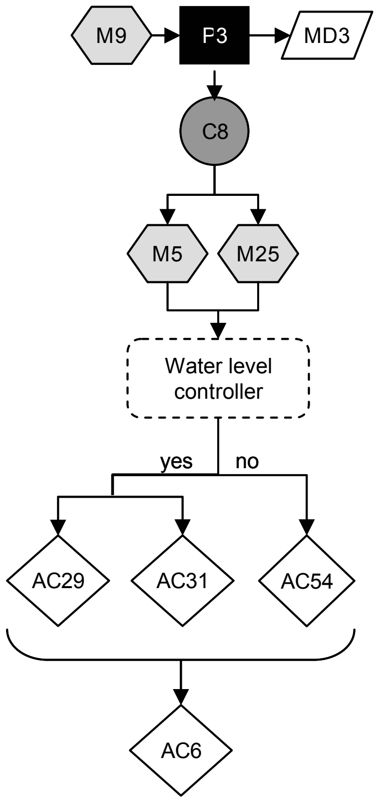

Figure 4.50. Decision tree for the diagnosis and solution of accumulation of vegetation debris over the HSCW surface {P3}.

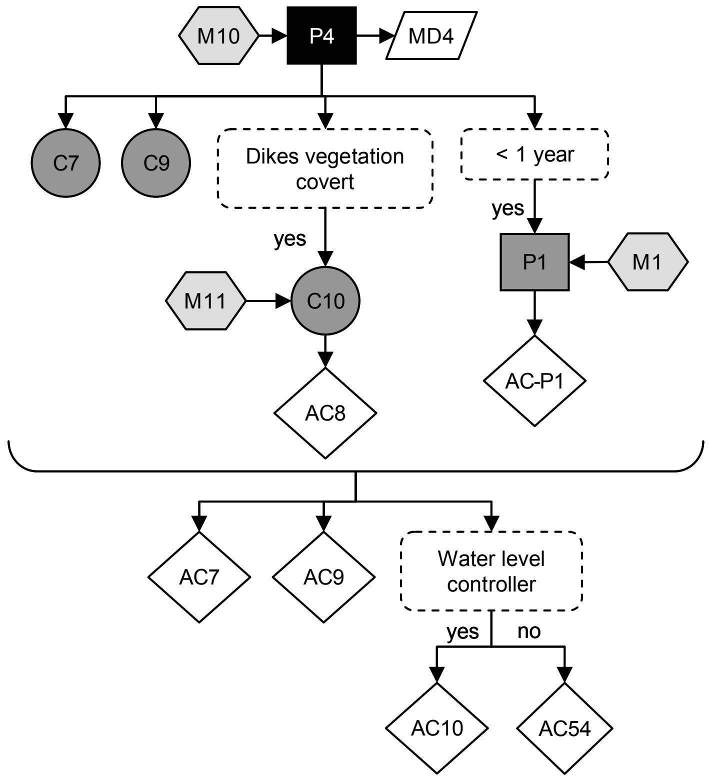

Figure 4.51. Decision tree for the diagnosis and solution of weeds growing on the HSCW {P4}.

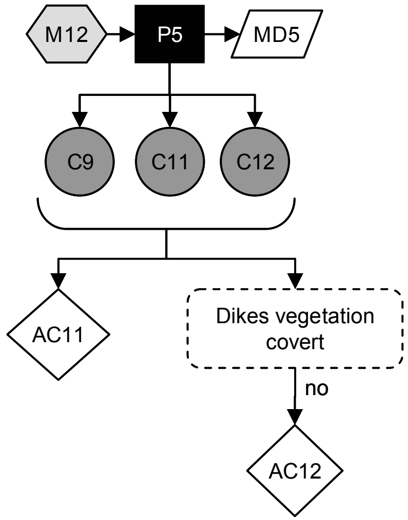

Figure 4.52. Decision tree for the diagnosis and solution of trees and/or bulrushes growing on and/or around the HSCW {P5}.

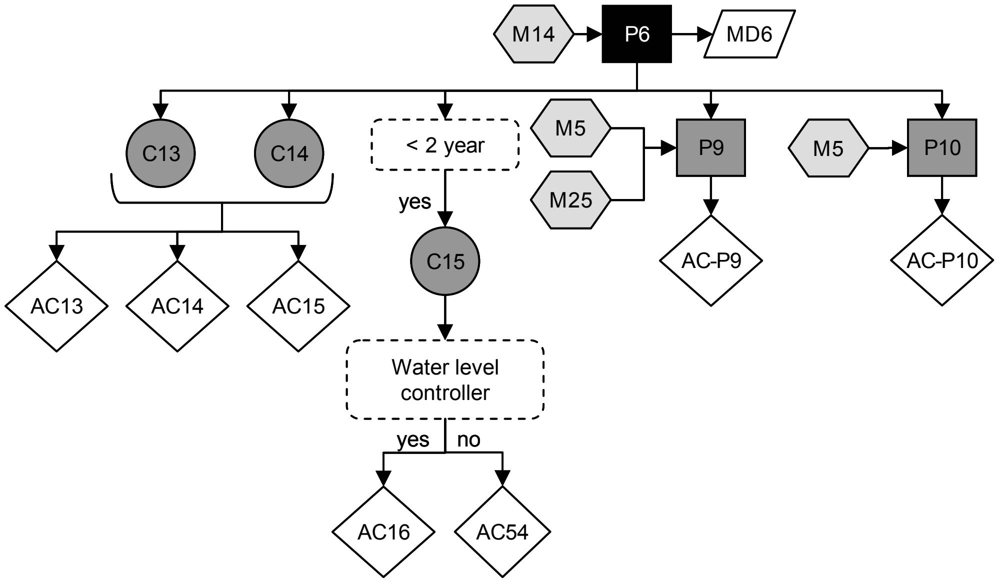

Figure 4.53. Decision tree for the diagnosis and solution of chlorosis {P6}.

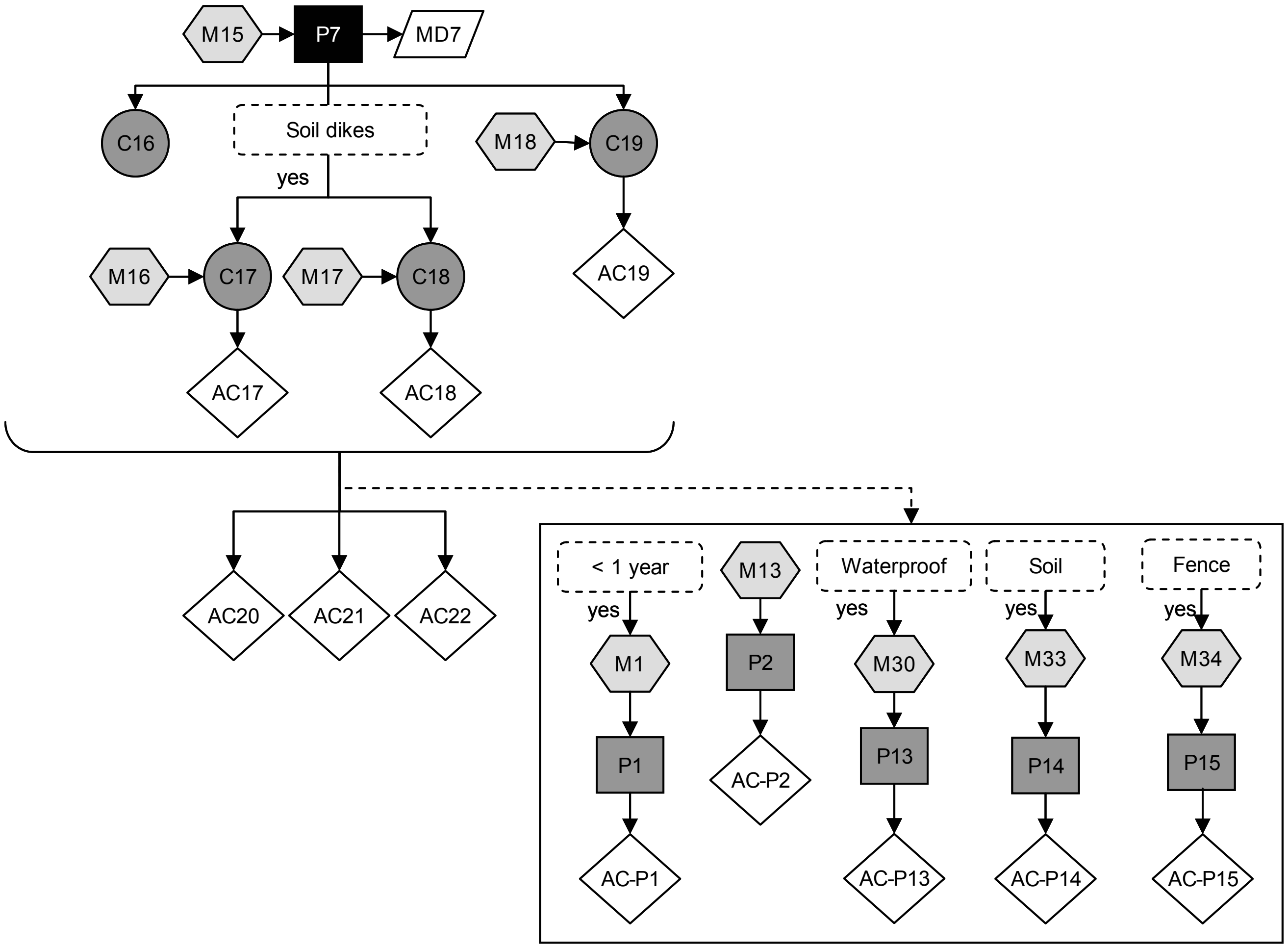

Figure 4.54. Decision tree for the diagnosis and solution of presence of rodents {P7}.

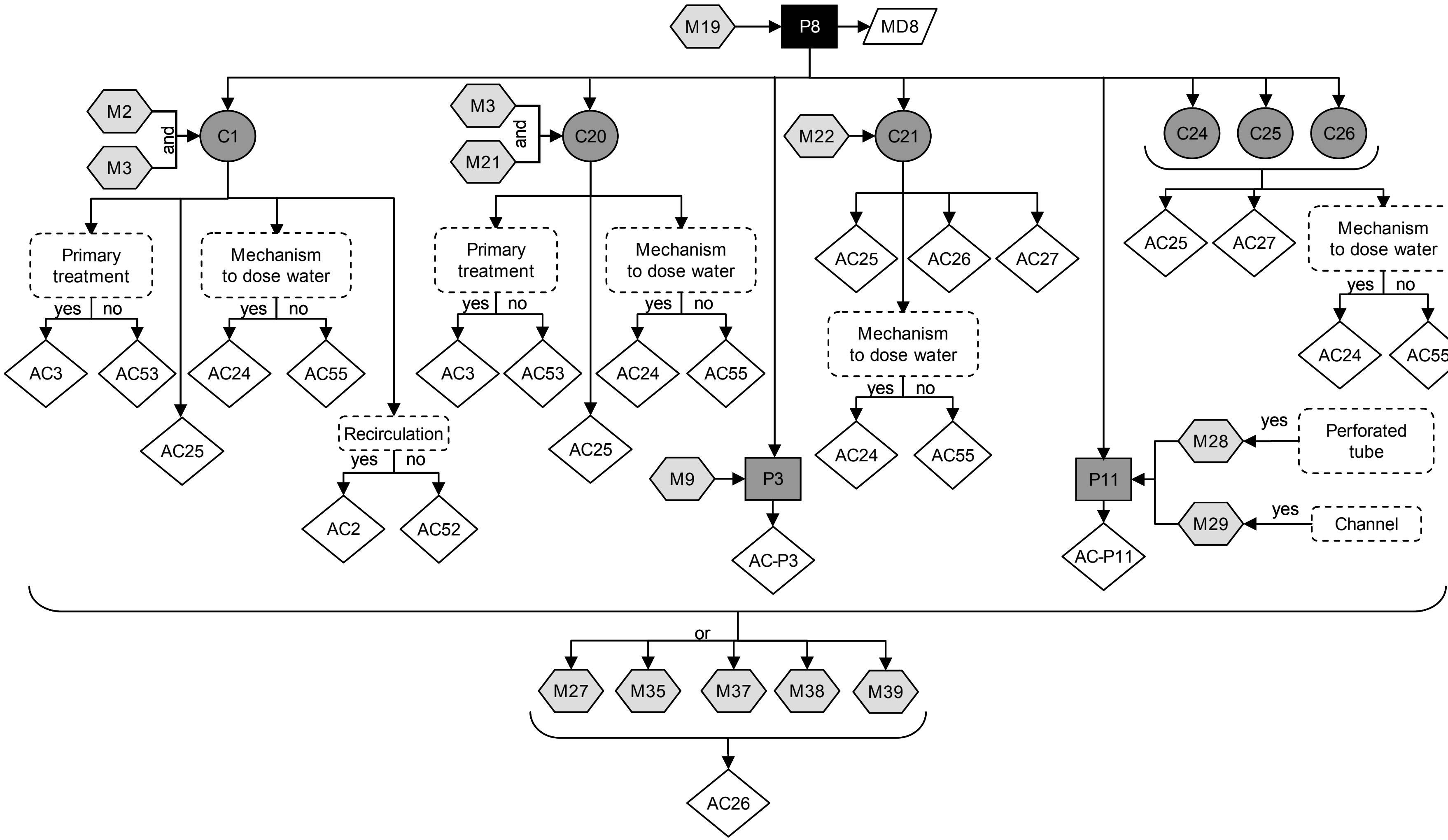

Figure 4.55. Decision tree for the diagnosis and solution of matrix clogging {P8}.

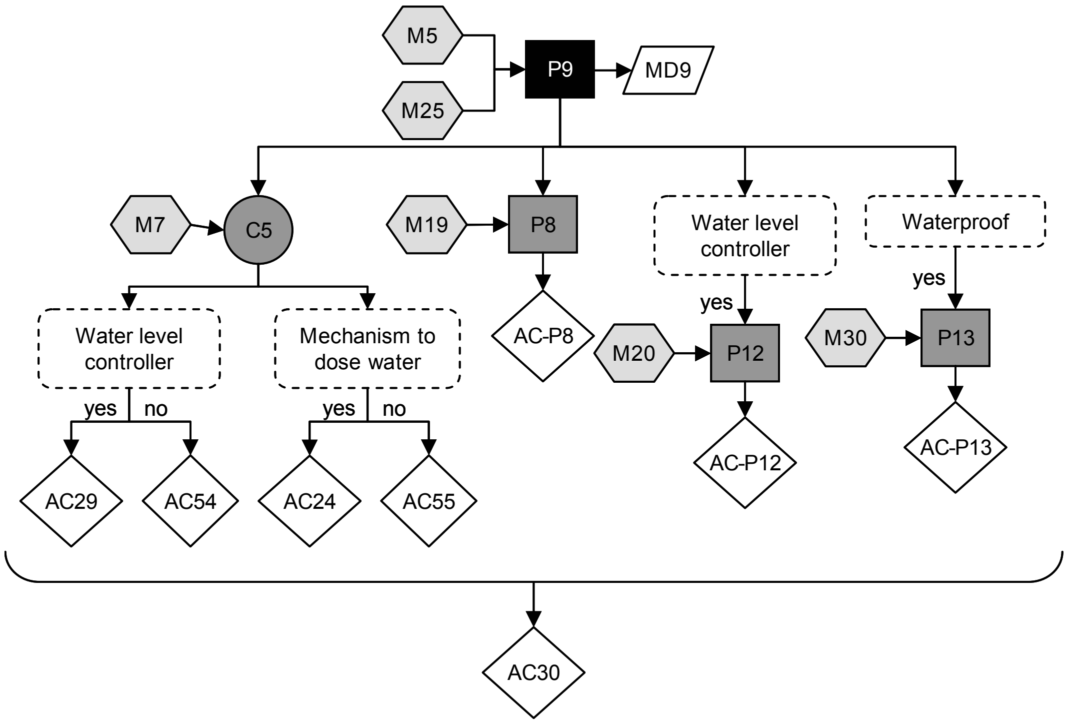

Figure 4.56. Decision tree for the diagnosis and solution of high water level or water flow over the matrix {P9}.

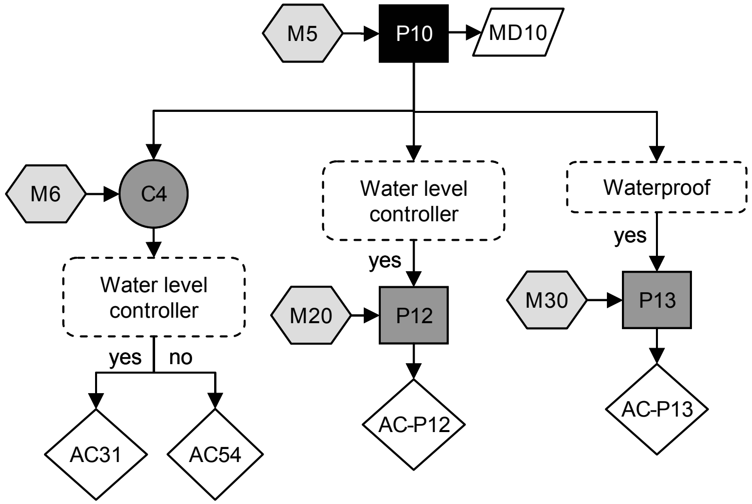

Figure 4.57. Decision tree for the diagnosis and solution of low water level {P10}.

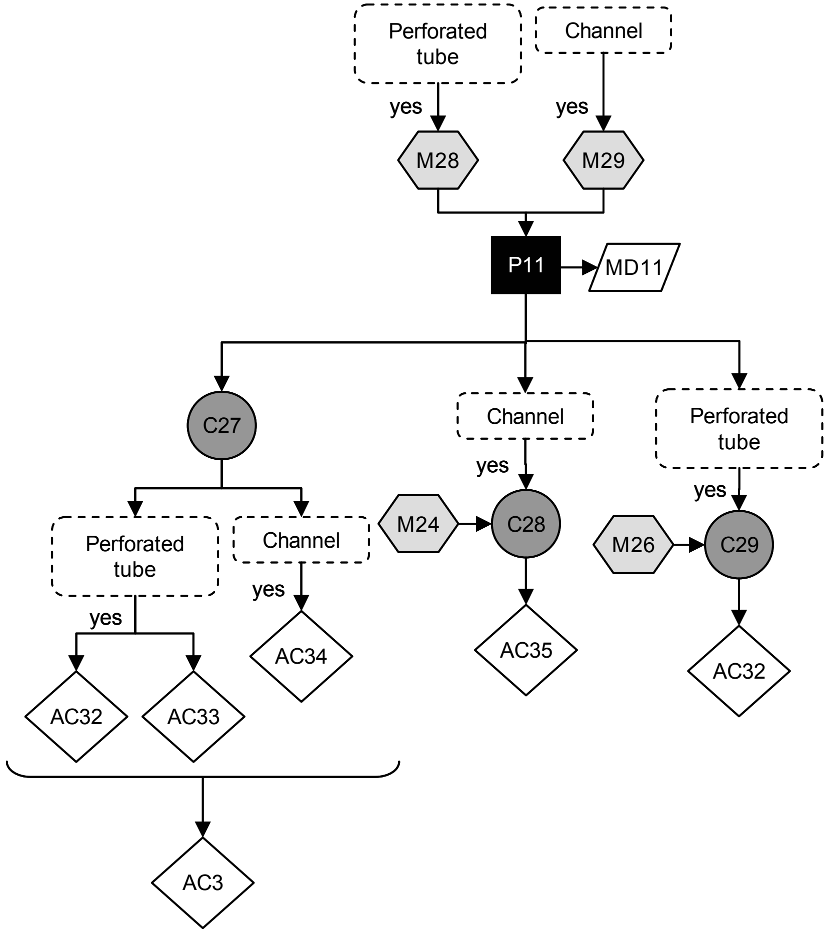

Figure 4.58. Decision tree for the diagnosis and solution of inappropriate water distribution {P11}.

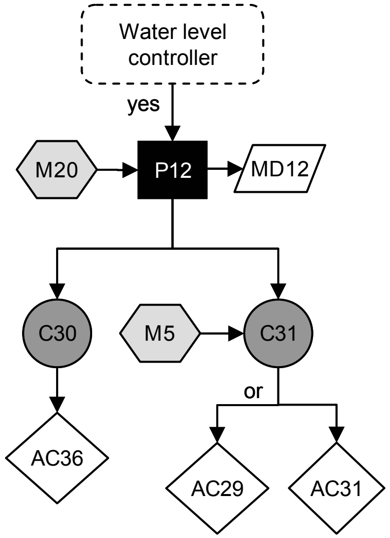

Figure 4.59. Decision tree for the diagnosis and solution of inappropriate water level controller regulation or maintenance {P12}.

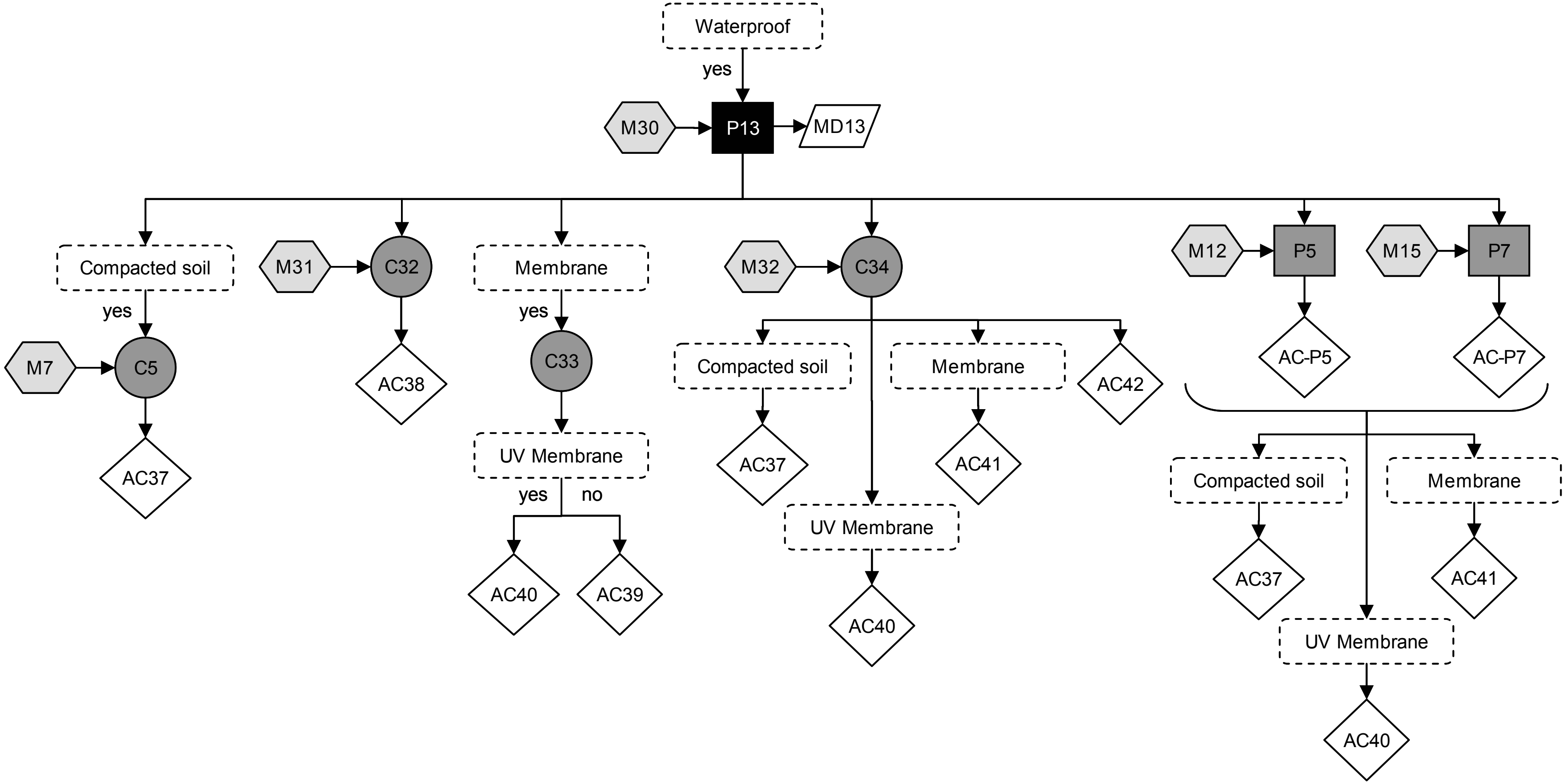

Figure 4.60. Decision tree for the diagnosis and solution of deficiencies in the waterproofing liner {P13}.

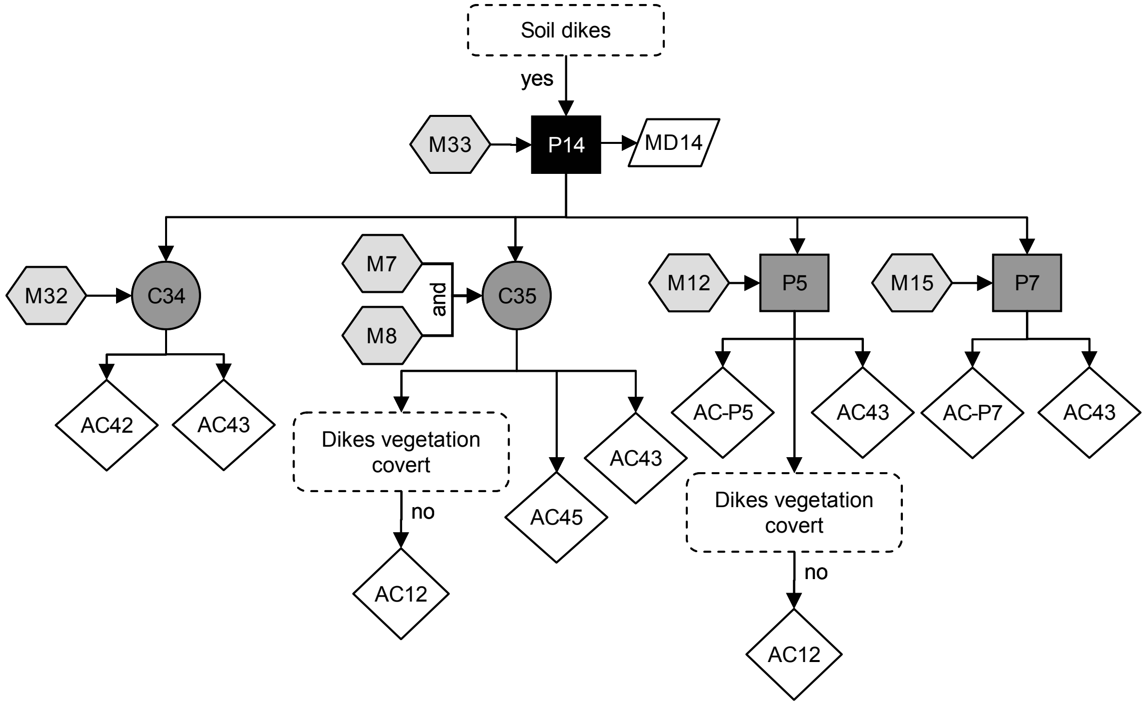

Figure 4.61. Decision tree for the diagnosis and solution of deficiencies in the dike structure {P14}.

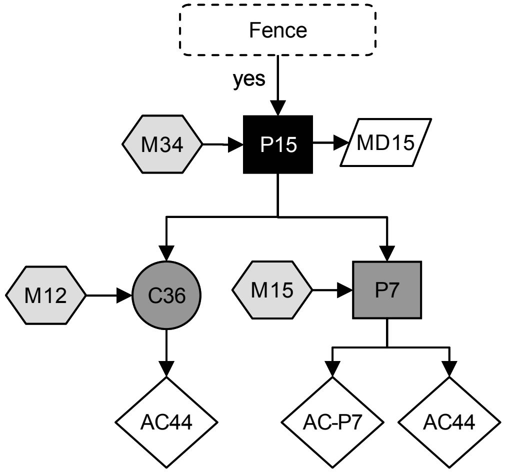

Figure 4.62. Decision tree for the diagnosis and solution of deficiencies in the fence {P15}.

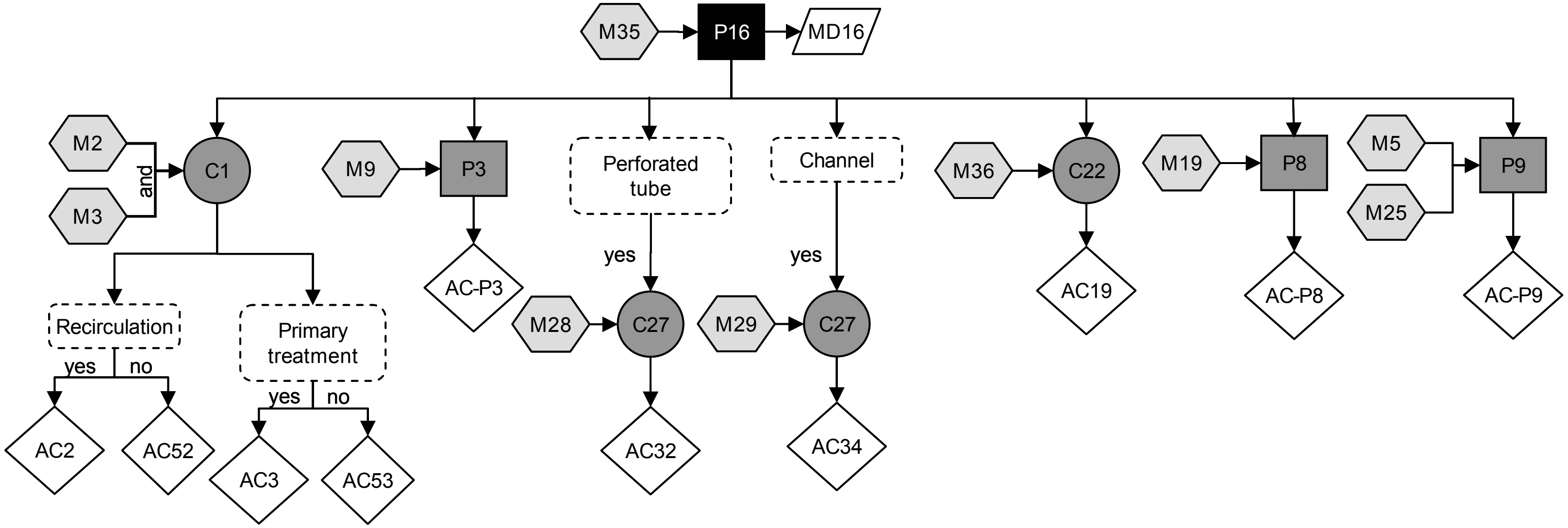

Figure 4.63. Decision tree for the diagnosis and solution of bad smells {P16}.

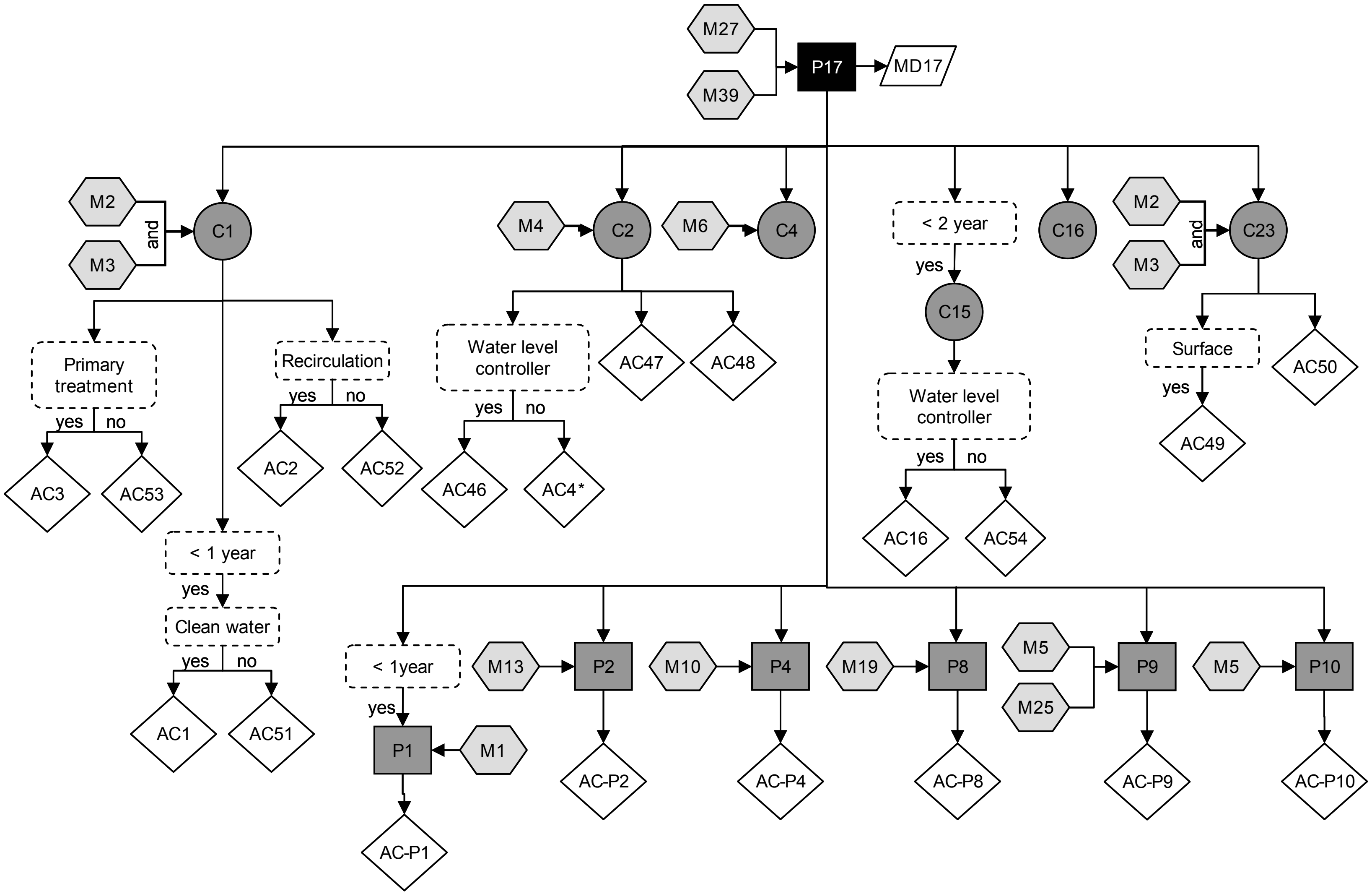

Figure 4.64. Decision tree for the diagnosis and solution of high concentration of organic matter in the effluent {P17}.

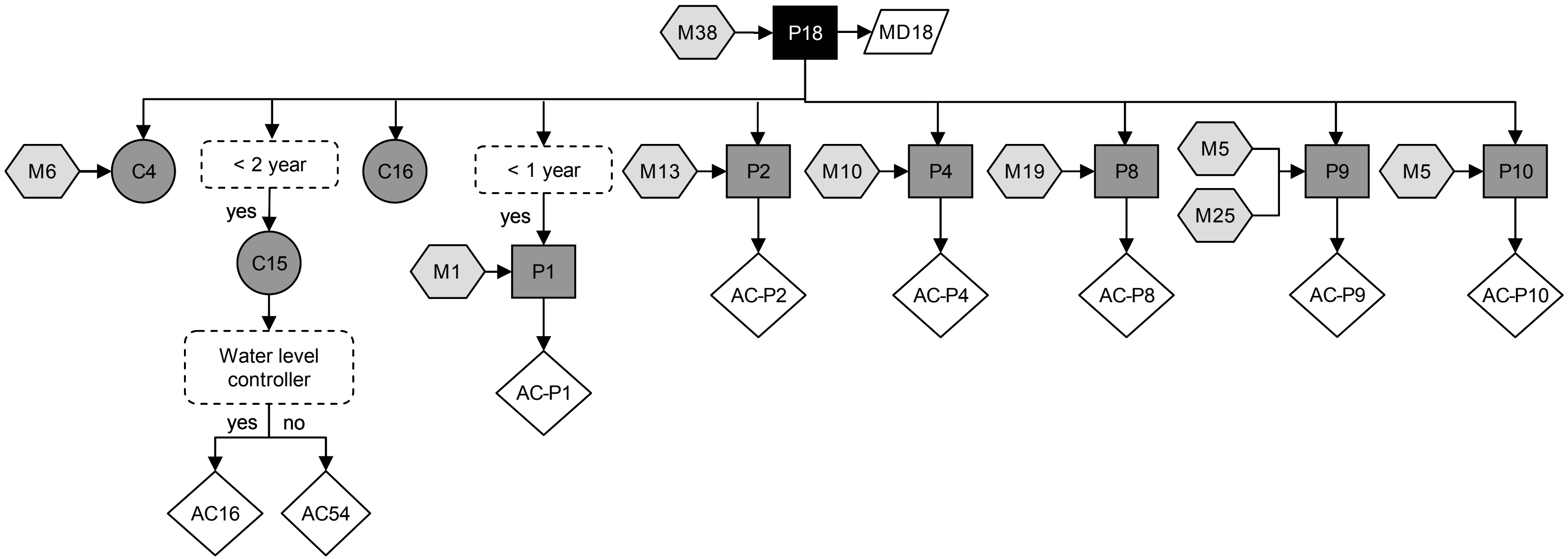

Figure 4.65. Decision tree for the diagnosis and solution of high concentration of suspended solids in the effluent {P18}.

4.4.1.2. Effect decision trees

The first step in the decision trees for predicting the effects of problems (Figure 4.66 – 4.83) is evaluation of the characteristics of the HSCW and the characteristics of the receiving media (⬚). From these properties, the effects (☐ and △) are predicted for a given problem (■).

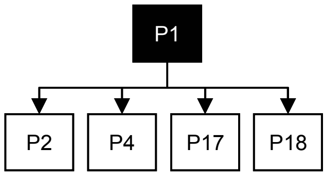

Figure 4.66. Decision tree for predicting the effects of problem {P1}.

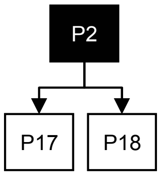

Figure 4.67. Decision tree for predicting the effects of problem {P2}.

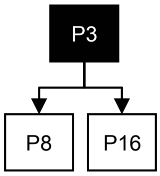

Figure 4.68. Decision tree for predicting the effects of problem {P3}.

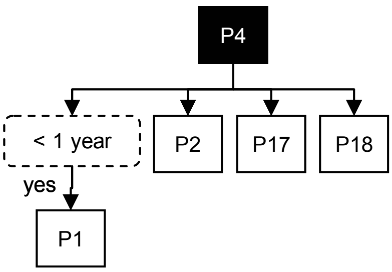

Figure 4.69. Decision tree for predicting the effects of problem {P4}.

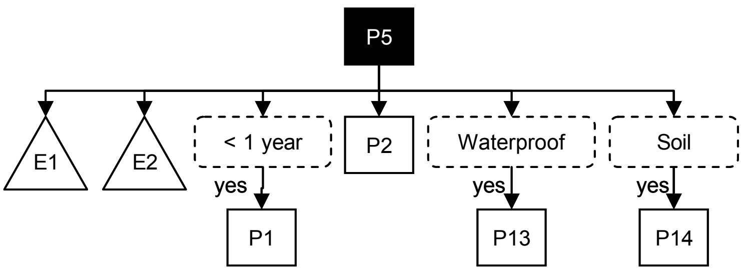

Figure 4.70. Decision tree for predicting the effects of problem {P5}.

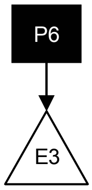

Figure 4.71. Decision tree for predicting the effects of problem {P6}.

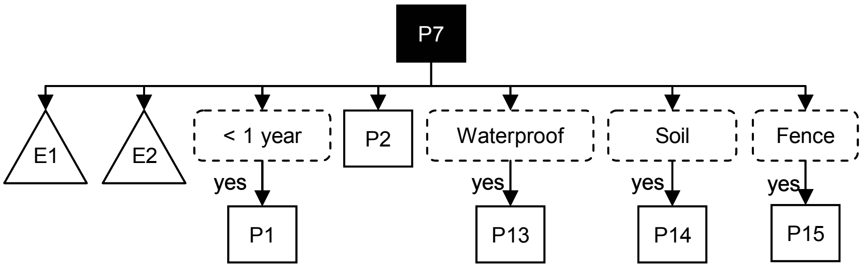

Figure 4.72. Decision tree for predicting the effects of problem {P7}.

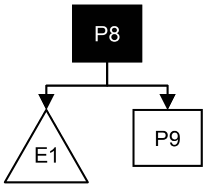

Figure 4.73. Decision tree for predicting the effects of problem {P8}.

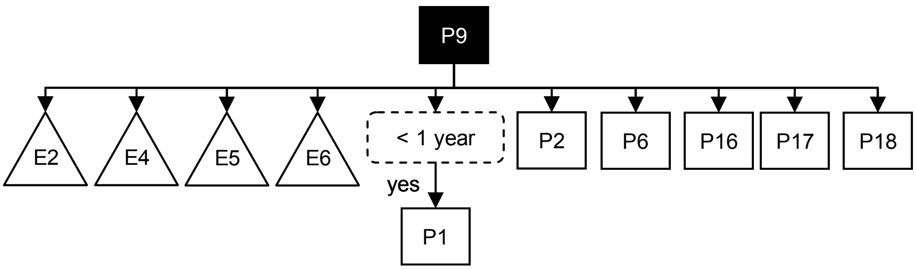

Figure 4.74. Decision tree for predicting the effects of problem {P9}.

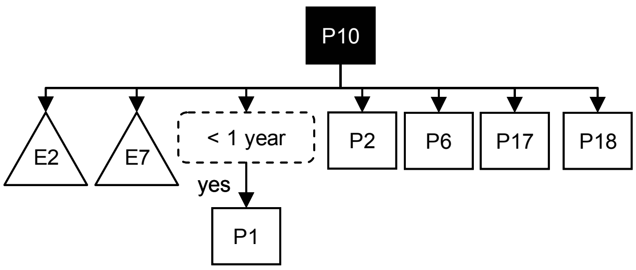

Figure 4.75. Decision tree for predicting the effects of problem {P10}.

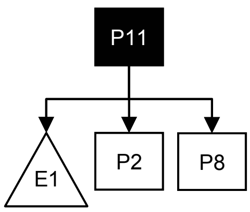

Figure 4.76. Decision tree for predicting the effects of problem {P11}.

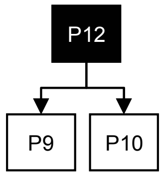

Figure 4.77. Decision tree for predicting the effects of problem {P12}.

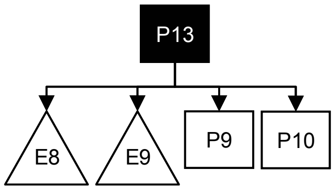

Figure 4.78. Decision tree for predicting the effects of problem {P13}.

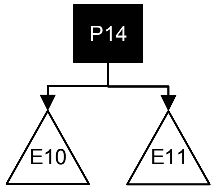

Figure 4.79. Decision tree for predicting the effects of problem {P14}.

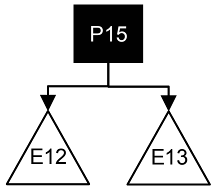

Figure 4.80. Decision tree for predicting the effects of problem {P15}.

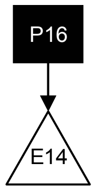

Figure 4.81. Decision tree for predicting the effects of problem {P16}.

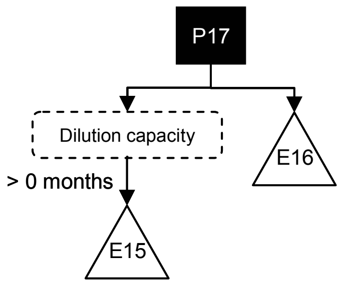

Figure 4.82. Decision tree for predicting the effects of problem {P17}.

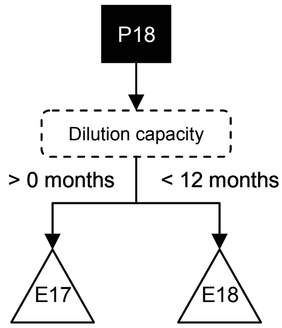

Figure 4.83. Decision tree for predicting the effects of problem {P18}.

4.4.1.3. Receiving media decision tree

To define the sensitivity of the receiving media, the following aspects are evaluated ( ):

- Dilution capacity or number of months in a year with certain water flow on the receiving media
- Soil and/or water nitrate pollution
- Protected landscape
- Presence of natural ponds or aquifers
- Existence of bathing zones or fishing areas

In accordance with these aspects, the receiving media are categorized into three levels of sensitivity: (1) very sensitive, (2) sensitive and (3) resistant ( ) (Figure 4.84).

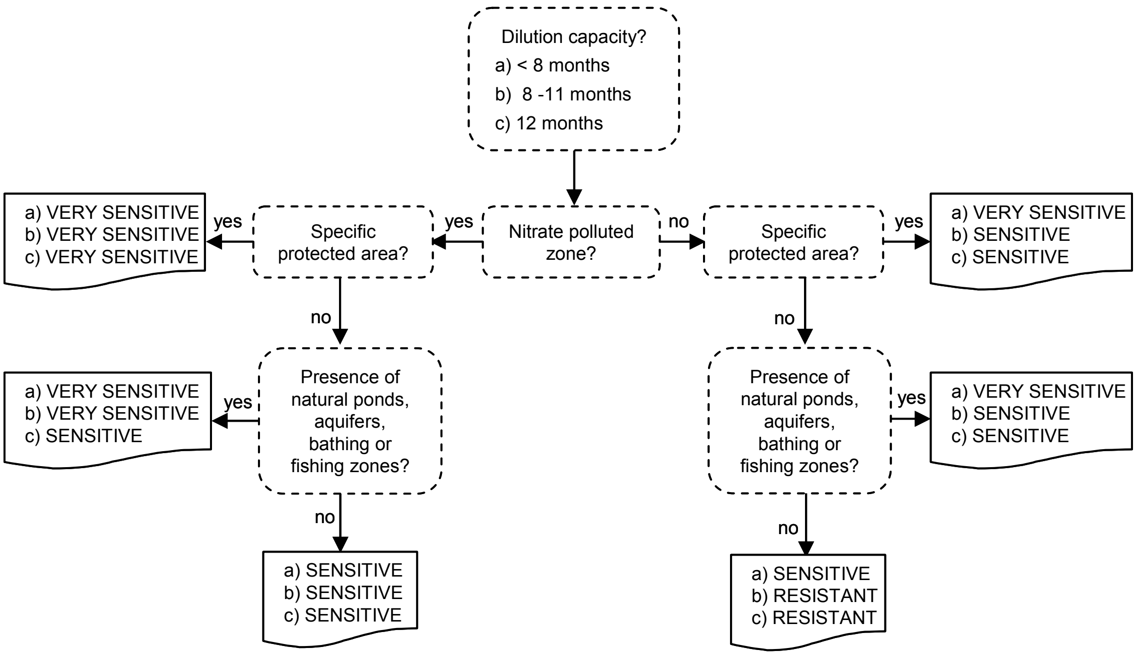

Figure 4.84. Decision tree with the reasoning path for categorizing the receiving media.

4.4.1.4. Frequency matrix

The frequencies of measures required to identify problems were organized in a matrix (Table 4.4) according to the sensitivity of the receiving media: Very Sensitive (VS), Sensitive (S) and Resistant (R). Moreover, this matrix includes the preventive action {AC56} to be carried out in all HSCWs at least once a year.

Table 4.7. Matrix summarizing recommended frequencies for the implementation of measures proposed for identifying problems and the preventive action.

Problem	Measure	Control frequency*[1]		
		VS	S	R
P1	M1: Visual control of vegetation to check growth of *Phragmites australis*	T	T	W
P2	M13: Visual control of vegetation to check the density and homogeneity of *Phragmites australis*	W	W	W
P3	M9: Visual control of HSCW surface to check accumulation of vegetation remains	W	W	W
P4	M10: Visual control of HSCW surface to check for weed growth	W*[2]	W*[2]	W*[2]
P5	M12: Visual control of HSCW surface and surroundings to check for growth of trees and bulrushes	M	M	M
P6	M14: Visual control of vegetation to check colour of *Phragmites australis*	W	W	W
P7	M15: Visual control of HSCW and surroundings to check for the presence of rodents	D	D	W
P8	M19: Visual control of HSCW to check for matrix clogging	D	D	W
P9	M5: Measure the water level on HSCW M25: Visual control of HSCW to check water flow over the matrix	D	D	W
P10	M5: Measure the water level on HSCW	D	D	W
P11	M28: Visual control of tubes to check the accumulation of solids M29: Visual control of channels to check for the accumulation of solids	D	D	W
P12	M20: Visual control of the water level controller to check its state and regulation	D	D	W
P13	M30: Visual control of waterproofing to check its state	W	W	W
P14	M33: Visual control of dikes to check their state	D	D	W
P15	M34: Visual control of fence and gate to check their state	W	W	W
P16	M35: Visit to facilities to check for bad smells	D	D	W
P17	M27: Measure the concentration of organic matter (BOD_5) of the effluent M39: Measure the concentration of organic matter (COD) of the effluent	W	F	M
P18	M38: Measure the concentration of suspended solids (SS) of the effluent	W	F	M
P_i *[3]	AC56: Cut the macrophytes	Y	Y	Y

*[1] VS: Very sensitive; S: Sensitive; R: Resistant; D: Daily; T: Two or three times a week; W: Weekly, F: Fortnightly; M: Monthly; Y: Yearly.
*[2] Weekly in springtime, fortnightly in summer and autumn, monthly in winter.
*[3] Preventive action to be applied whatever the characteristics of the HSCWs and independently of the problems detected.

The representation of HSCW knowledge in decision tree and matrix form does not provide us with extra information. However, this visual representation does facilitate (1) the understanding of HSCW knowledge, (2) the definition of the relationships between problems and (3) the revision of knowledge. Moreover, knowledge represented in decision trees and matrices can be then simply converted into IF-THEN rules by traversing each branch from the root to the leaf or crossing from the columns to the rows.

4.4.2. Knowledge codification

The knowledge integrated within EDSS-maintenance was translated into IF-THEN rules using Java language. Figure 4.85 provides an example of a rule for the problem {P1} - Abnormal vegetation growth during start-up.

```
<rule name="p1_condicional_4">

    <parameter identifier="raonament">
            <class>
               raonament_1
            </class>
    </parameter>

    <java:condition>
            raonament.sobrecarrega_organica == true
    </java:condition>

    <java:condition>
            raonament.deficient_creixement_posada_marxa == true
    </java:condition>

    <java:consequence>
            raonament.activar_llistat_accions_p1_c1()

            <java:condition>
                    raonament.aigua_neta == true
            </java:condition>

            <java:consequence>
                    raonament.afegir_llistat_accions_p1_c1(ac1)
            </java:consequence>

            <java:condition>
                    raonament.aigua_neta == false
            </java:condition>

            <java:consequence>
                    raonament.afegir_llistat_accions_p1_c1(ac51)
            </java:consequence>

            ...

    </java:consequence>


    </java:consequence>

</rule>
```

Figure 4.85. Example of a rule: identification of problem {P1} and its causes and proposal of a measure to identify the problem.

Revision and upgrading (where necessary) of the knowledge base was facilitated by grouping rules into nineteen sets (modules):

- **Receiving media sensitivity:** This group includes the three rules that allow the sensitivity of the receiving media to be defined according to its dilution capacity or months of a year that there is some water flow:
  - Regular flow: 12 months a year
  - Seasonal flow: from 8 to 11 months a year
  - Irregular flow: fewer than 8 months a year

  Every rule verifies six facts (nitrate pollution, specific protected area, and presence of natural ponds, aquifers, fishing areas and bathing zones). The sensitivity of the receiving media is defined from these aspects (Figure 4.82).

- **Problems:** The other rules are organized into 18 groups to identify and characterize the 18 problems associated with HSCWs (one group of rules per problem). In each group it is possible to distinguish four types of rules:
  - The first rule codifies the knowledge to identify (1) the problem, (2) the modes, (3) the measures required to recognize the problem and (4) the causes.
  - Then there is a rule that permits defining of the frequency with which the measure to identify the problem must be implemented.
  - Subsequently there are other rules which propose measures to identify the causes and actions for solving the problem, depending on its origin (one rule for every cause).
  - Finally, there is a rule that identifies the predicted effects on the environment.

It is important to remark that, apart from these nineteen sets of rules, there is another group which allows the input data and intermediate results to be acquired from the working memory. Hence, this last set of rules is the starting point for the process which allows a proposal to the solution.

4.4.3. Recommendations to build the full EDSS-maintenance

Decision trees and matrices reliably represented HSCW knowledge and, in addition, eased the codification of the heuristic rules. Hence, we propose using these representations for all the wastewater treatment technologies. But if numerical information is required to characterize problems, mathematical equations to represent this information are recommended.

The EDSS-maintenance prototype was built using a single model: RBS, hence no model integration has been required. Whenever the development of the full EDSS-maintenance requires more than one model, the model integration will be needed. When this integration is in series (the output of one model is the input of the following one) the format of the data must be verified to avoid format inconsistencies between models. On the other hand, when the integration is in parallel (two models or more work simultaneously to obtain a result) the effort must be focused on (a) avoiding conflicting results (e.g. two models provide a contradictory result from the same input data) and (b) confronting the different temporality scales (e.g. a daily and a continuous online measure).

4.5. Evaluation process

Environmental problems are usually *ill-structured* and no efficient algorithmic approach is known for them. Humans solve these problems using knowledge and previous experience. The combination of these two aspects is called expertise, and is very important to efficiently achieve an acceptable solution. EDSSs are environmental problem solvers for specialized domains of competence. These decision support systems allow the expertise in the process to be integrated to reach an effective solution to the problem. Assuring the reliability of EDSSs has been always a crucial issue because of the importance of the tasks they perform.

In general, the evaluation process of a product consists in checking that this product is fully operational and satisfactorily performs its intended function. When applied to software, the evaluation process aims to check that programs are free of errors and satisfy the users' needs.

Currently, the degree of evaluation reachable in EDSSs is far below the degree attainable in conventional software because, while the EDSS programming is concerned with truth values, rule dependencies and heuristic associations, the conventional programming deals with variables, conditionals, loops and procedures. In consequence, better evaluation methods and techniques are required, with the final aim of achieving for EDSSs the confidence level that is currently available for conventional software. With this panorama in mind, we proposed an *ad hoc* evaluation method based on interaction with human experts in the field.

The methodology proposed to evaluate the EDSS-maintenance is an iterative procedure occurring throughout the system development. This process has to guarantee both the correct functioning of the EDSS-maintenance prototype and the compliance with the user requirements:

(1) Identify the HSCW's problems.

(2) Identify the causes unleashing these disturbances.

(3) Propose the most appropriate corrective actions.

Hence, the objective of this evaluation process is to check the robustness, accuracy, usefulness and usability of EDSS-maintenance.

At the time of writing this thesis, the robustness and the accuracy have been evaluated. No advances have been made in the evaluation of the EDSS-maintenance in terms of usefulness and usability because only the first step of the evaluation process (Laboratory testing – 3.5. Evaluation process) has been completed.

Despite the definition of the laboratory testing [Comas (2000)], there is no detailed protocol on how to proceed with the verification and laboratory validation of decision support systems because such tools (1) combine different models, analytical techniques and information retrieval methods to (2) handle complex and poorly structured problems [Sojda (2004) and Sojda (2007)]. Many techniques have been proposed, developed and implemented [Ayel and Laurent (1991), Lydiard (1992), Meseguer and Verdaguer (1993), O'Keefe and O'Leary (1993), Rosenwald and Liu (1997), Tsai *et al.* (1999) and Preece (2001)], but there is no consensus on the definition (type and number) of the series of experiments to verify the correct performance of the system and the specification (type, number, duration…) of the sequence of case studies to check the adequacy of EDSS proposals. Moreover, there are no clear guidelines to benchmark and quantify how accurate an EDSS is.

The following sub-sections (4.5.1. Verification and 4.5.2. Laboratory validation) present: (1) the methodology used in the verification and the laboratory validation of EDSS-maintenance and (2) the results obtained in both evaluation procedures.

4.5.1. Verification

The verification process refers to building the system "*right*" [O'Keefe *et al.* (1987) and Preece (2001)], substantiating that the system correctly implements its specifications [González and Dankel (1993)]. In other words, verification can be defined as the procedure to check the specifications of the system: consistency and completeness. Hence, the verification procedure of EDSS-maintenance involves two steps: 4.5.1.1. Checking for consistence and 4.5.1.2. Checking for completeness.

Despite the existence of tools to automatically perform the verification process of RBS by comparing premises and conclusions of each rule individually with all the others, comparing premises of one rule with all the others, comparing conclusions of one rule with all the others and comparing all the premises with all the conclusions, the verification of EDSS-maintenance was done manually because little is known about the effectiveness of these automatic verification and validation techniques [Preece (2001)]. Besides, not only is it important for a decision support system to handle common cases, but the EDSS must be also able to deal with extreme events that often drive ecological systems. This ability is often only characteristic of human experts [Sojda (2004) and Sojda (2007)] and, therefore, it can only be verified by experts.

The verification process of EDSS-maintenance started with the implementation of the first rule and lasted until all the rules were codified. Each one of the rules was submitted to the verification process at three levels:

(1) Individually.

(2) As a member of a group of rules. The rules were grouped in 20 clusters during the codification (4.4.2. Knowledge codification).

(3) As a rule of the entire EDSS-maintenance.

4.5.1.1. Checking for consistence

Checking for consistence in the knowledge base of the RBS implies checking for syntactic and semantic errors that the developers often introduce during the development phase. During the verification of decision trees the base of heuristic rules was checked for the existence of the following types of erroneous rules:

(1) Redundant rules: Redundancy occurs when the RBS contains components which can be removed without affecting the behaviour of the system [Preece and Shinghal (1994)]. Among redundant rules it is possible to differentiate:

a. Subsumed rules: One rule is subsumed by another one if it has more constraints in the premise while having identical solutions (i.e. IF p and q THEN r – IF p THEN r) [Comas (2000)].

IF *[< P1 – Abnormal vegetation growth during the start-up >*
and
< M1 – Verify the state of the vegetation during the start-up >
and
< receiving media is resistant >]
THEN *< the frequency of M1 is weekly >*

IF *[< M1 – Verify the state of the vegetation during the start-up >*
and
< receiving media is resistant >]
THEN *< the frequency of M1 is weekly >*

In this example the rule in the first box is subsumed by the rule in the second one because the former has more constraints than the latter.

b. Unnecessary IF conditions: Similar to subsumed rules.

IF *[< dilution capacity is lower than 8 months >*
and
< is a nitrate polluted area >
and
< is a specific protected area >]
THEN *< the receiving media is very sensitive >*

IF *[< dilution capacity is lower than 8 months >*
and
< is not a nitrate polluted area >
and
< is a specific protected area >]
THEN *< the receiving media is very sensitive >*

The premises of these rules are identical except one in each rule that is contradictive. If the second premise of each rule is truly unnecessary, these two rules can be collapsed into the single rule:

***IF** [< dilution capacity is lower than 8 months >*
and
< is a specific protected area >]
***THEN** < the receiving media is very sensitive >*

(2) Conflicting rules: Conflict occurs when it is possible to derive incompatible information from a valid input (i.e. IF p THEN q – IF p THEN not q) [Preece and Shinghal (1994)].

***IF** < HSCW is less than 1 year old >*
***THEN** < P1 – Abnormal vegetation growth during the start-up is TRUE >*

***IF** < HSCW is less than 1 year old >*
***THEN** < P1 – Abnormal vegetation growth during the start-up is FALS >*

(3) Circular rules: Circularity occurs when a chain of inference in a knowledge base forms a cycle (i.e. IF p THEN q – IF q THEN p) [Preece and Shinghal (1994)]. In other words, circularity occurs when a set of rules lead to an infinite loop of useless rule firings. In forward-chaining systems this error is rarely checked if rule conclusions have been previously derived [Comas (2000)].

***IF** [< dilution capacity is 12 months >*
and
< is a nitrate polluted area >
and
< is a specific protected area >]
***THEN** < the receiving media is very sensitive >*

***IF** < the receiving media is very sensitive >*
***THEN** [< dilution capacity is 12 months >*
and
< is a nitrate polluted area >
and
< is a specific protected area >]

4.5.1.2. Checking for completeness

Checking for completeness of the RBS implies checking whether all items that should be in the operation and maintenance protocols are included. Therefore, the RBS was checked for the existence of the following types of errors [Comas (2000)]:

(1) Dead-end rules: Rules that have actions that do not affect any conclusions and are not used by other rules to generate any other conclusions.

> ***IF*** *< the plantation density of* Phragmites australis *is 4 plants·*m^{-2} >
>
> ***THEN*** *< the plantation density is normal >*
>
> None of the rules use the premise:
> *IF < the plantation density is normal > THEN*

(2) Unreachable rules: Rules with a premise that will never be matched.

> ***IF*** *[< water level is HIGH >*
> ***and***
> *< water level is LOW >]*
> ***THEN*** *< the water level is inappropriate >*

(3) Missing rules: Rules characterised by facts that are not used in the inference process and conclusions that do not affect any other rule procedure.

4.5.1.3. Verification results

During the verification process the rules were tested, revised and sometimes reformulated to accomplish the requirements of the EDSS-maintenance prototype. Despite there not being a detailed report of the changes done during this process, the following aspects can be highlighted:

- **Consistence:**
  - Earliest errors in the RBS implementation were related to the use of symbols, articles, conjunctions, etc. used in the knowledge codification. These syntax errors were mainly found while checking for consistency of the rules during the consistence checking of the rules as individual components of EDSS-maintenance.
  - Even though the semantic evaluation of rules started with checking rules individually, the first semantic errors were found when rules were verified as members of a group of rules or of the whole EDSS-maintenance. The great majority of identified errors were redundant rules, both subsumed rules and unnecessary IF conditions.
  - Another relevant aspect of this verification sub-stage was the identification of an error category not defined during the literature revision: rules with imprecise premise definitions. This new typology of error can be also considered as a completeness error because, as a consequence of inappropriate syntax and semantic content, the system can be over-completed or can provide wrong recommendations.

    For instance, {C1} can be the origin of five different problems: {P1}, {P2}, {P8}, {P16} and {P17}. In the first EDSS-maintenance prototype if the rules of two of these problems were fired, then the

EDSS-maintenance provided recommendations by duplicate (Figure 4.86, a). That is the case when {P2} and {P16} rules were fired. The first rule of problem {P2} (Rule 1 - Problem {P2} in Figure 4.86, a) activated the second one (Rule 2 - Problem {P2} in Figure 4.86, a). An identical procedure happened with the rules of problem {P16}. Nevertheless, the first rule of problem {P2} could fire the second rule of problem {P16}, providing duplicity of corrective actions: {AC2} appeared twice in the operation and maintenance guidelines for problem {P2}. The same inconsistency was observed in problem {P16}. This error was solved redefining the conclusions of Rule 1 and the premises of Rule 2, i.e. defining a vector [V_i , V_{i+1}, … V_n] and setting a different position of object {C1} in this vector and/or adding a new premise to it (Figure 4.86, b).

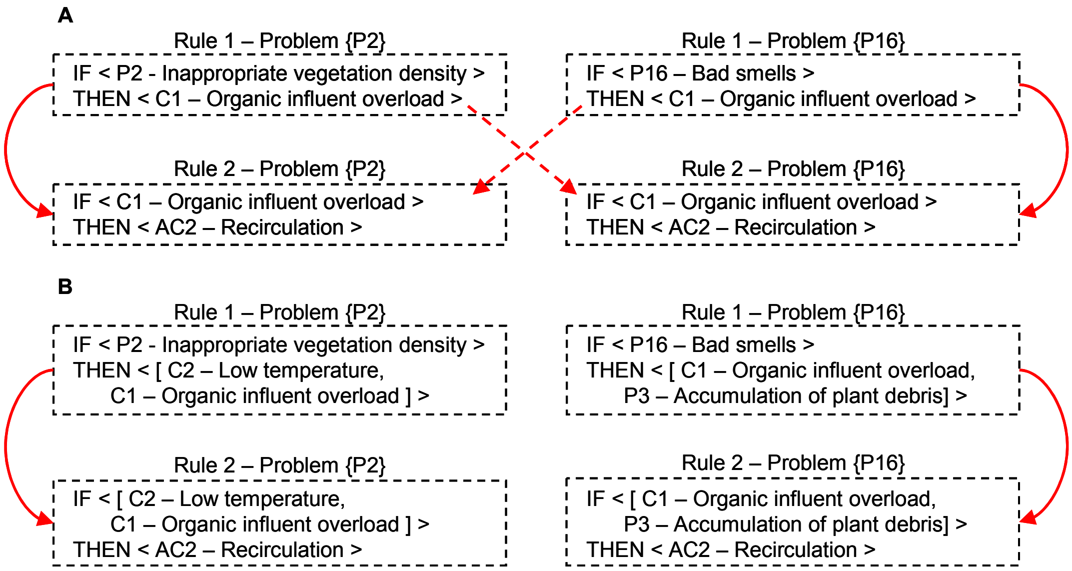

Figure 4.86. Example of imprecise rule definition causing an over-complete system (A) and the solution adopted to confront this inconsistency (B).

In the same framework of {C1}, if the first EDSS-maintenance prototype provided a protocol for a HSCW older than one year, the vague premise definition led to wrong results (Figure 4.87, a). The first rule of problem {P16} could fire the third rule of problem {P1}, while the first and second rules of {P1} were not fired because {P1} only appears in those HSCWs that are less than one year old. As a consequence of this inconsistency, the corrective action {AC1} appeared in the operation and maintenance guidelines, but this action is only recommended when the HSCW is less than one year old. Again, this error was also solved defining a vector [V_i , V_{i+1}, … V_n] in the conclusions of Rule 2 – Problem {P1} and Rule 1 – Problem {P16} and in the premises of Rule 3 – Problem {P1} and Rule 2 – Problem {P16} (Figure 4.87, b).

- **Completeness:**
  - Completeness was evaluated during the verification process but accurate verification of the items started once the rules were considered as members of a set of rules because it was better to check then if all operation and maintenance items were included in protocols.
  - No completeness errors were detected; all premises can be matched and conclusions provide the modes, effects, causes, measures and actions that have to be included in the operation and maintenance protocols.

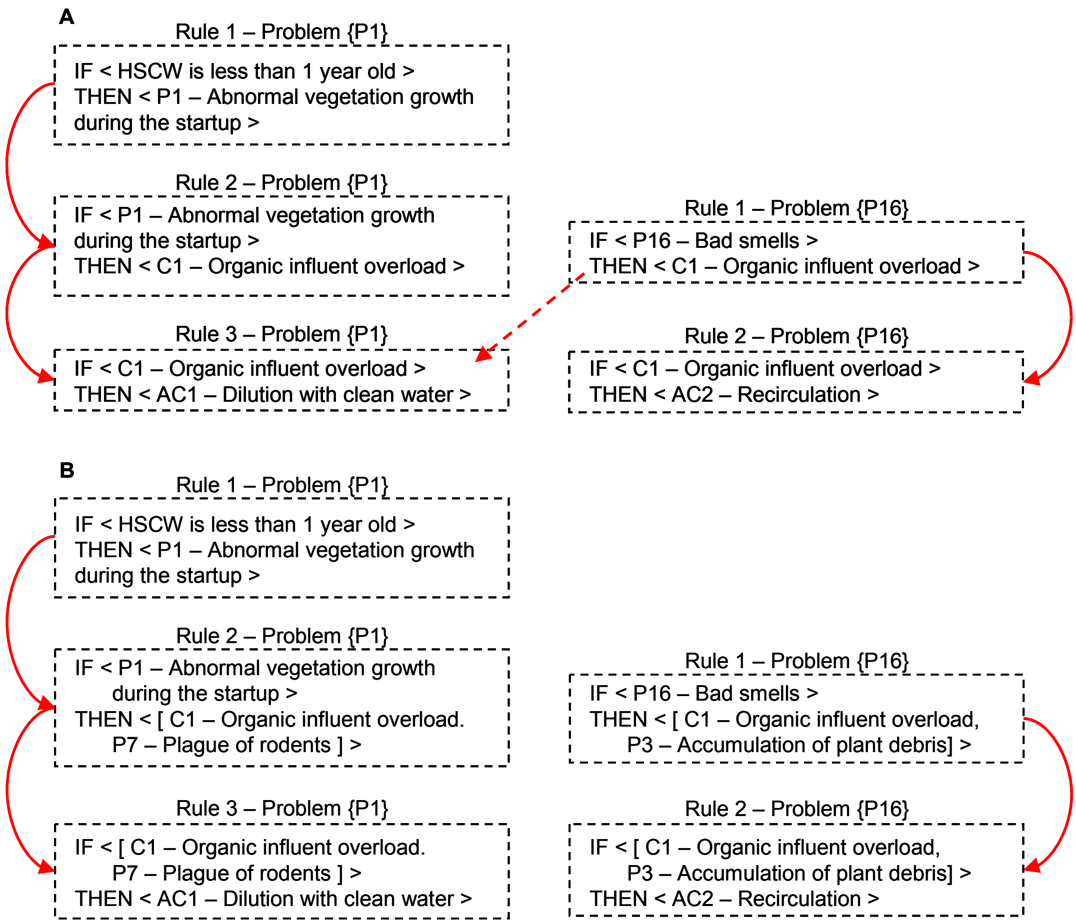

Figure 4.87. Example of imprecise rule definition causing a wrong recommendation (A) and the solution adopted to confront this inconsistency (B).

4.5.2. Laboratory validation

The validation process refers to building the "*right*" system [O'Keefe *et al.* (1987) and Preece (2001)]. Hence, validation is the process of checking (1) whether or not the content of the knowledge base accurately represents the knowledge of experts and (2) whether the system achieves the requirements of users [Preece (2001), Sojda (2004) and Sojda (2007)]. These requirements could involve taking better decisions, avoiding poor ones, or helping the user take them faster or with less data, information and knowledge [Sojda (2007)].

To avoid the unintended situation where software provides expected outputs simply via the calibration and correlation of inputs and outputs, rather than via scientific and logical relationships, validation must occur after verification [Mihram (1972), Adrion *et al.* (1982) and Sojda (2007)].

One way to validate the entire input domain of an RBS is to test all possible input scenarios. However, exhaustive testing is most often not feasible due to the large (potentially infinite) number of test cases that must be considered. Normally, a reduced number of test cases is selected [Rosenwald and Liu (1997) and Sojda (2007)]. In the validation of the EDSS-maintenance prototype the following test cases were selected [Turon *et al.* (2006 c)]:

- **Historical data sets:** Despite it being recommended to build the system using data and knowledge from one set of situations and validate it using an independent set [Sojda (2007)], the lack of HSCW historical data leads to comparing the operation and maintenance tasks proposed by EDSS-maintenance for the thirteen HSCWs located in Catalonia, with the actual operation and maintenance protocols applied in these facilities (4.2.1. Data and knowledge acquisition).

- **Panel of experts:**
  - Laboratory scale: The EDSS-maintenance prototype was applied to the 31 HSCWs planned for the Fluvià River basin in the PSARU 2002 project [Alemany *et al.* (2005)]. These protocols were evaluated by a panel of experts not connected to system development: Carlos Arias (University of Aarhus), Joan García (Technical University of Catalonia) and Antonina Torrens (University of Barcelona).
  - Field scale: The last test case will be performed in the near future when the protocols provided by the EDSS-maintenance will be applied to full scale HSCWs. The technicians of these HSCWs will be responsible for evaluating the usefulness of the protocols.

Validation is typically subjective because formally-represented knowledge is compared to informal statements [Preece (2001)]:

(a) In the historical data test, the EDSS-maintenance protocols were compared with real protocols which guarantee the HSCW performance but might not be 100% correct.

(b) In the laboratory-scale validation, the experts evaluated the protocols based on their experience. As a consequence, the validation results for a given protocol can vary among experts.

(c) In the field-scale validation, the technicians will base the evaluation of protocols on the HSCW performance and the capacity of these facilities to achieve the required treatment levels.

This subjectivity aroused a complex dilemma: how to quantify how “good” the EDSS-maintenance is. To confront this complexity and to measure the usefulness of an EDSS, we propose the following mathematical equation (Equation-1), which compares the EDSS results with (1) historical data and (2) an optimal situation (defined from the expert experience).

$$V\ (\%) = \left(\frac{\sum_{j=1}^{j=n} R_j\ EDSS}{\sum_{j=1}^{j=n} R_j\ real} \right) \cdot 100$$

Equation-1

Where:

V: Capability of the system to find the most appropriate solution.

R_j *EDSS:* Results proposed by the EDSS. Results can be problem diagnoses, cause identification, solution proposals, etc. according to the purpose of the validation.

R_j *real:* Results in a real case (according to historical data or experts’ experiences).

n: number of cases evaluated.

When the EDSS covers the expected results, V is 100%. If V is lower than 100%, it means that the EDSS omits some of the expected results. On the contrary, if V is higher than 100%, it indicates that the EDSS provides more information than expected.

It is necessary to pay special attention when V is 100% because it could be caused by compensation phenomena. For instance, EDSS-maintenance can identify two problems that are not included in the list of problems detected by an HSCW operator. On the other hand, an HSCW technician can identify two problems that are not included in the knowledge base of the EDSS-maintenance. Therefore, considering only the number of problems identified by both the EDSS and the technician, V will be 100% but the EDSS will not cover all the expected results. Hence, the comparison of EDSS and real case results has to be done in terms of quantity ("number" of results) and quality ("type" of results).

Once the validation procedure gives evidences of a lack of knowledge (i.e. V < 100%) or, on the contrary, useless information (i.e. V > 100%), an in-depth study has to be performed to analyse the knowledge base. The purpose of this knowledge revision is to asses whether or not the knowledge base has to be modified. To facilitate the decision about removing or including knowledge, we proposed another mathematical equation that considers the probability that a result provided by the EDSS can be found in (1) historical cases, (2) expert experiences and (3) the EDSS proposals (Equation-2). Equation-2 allows the probability that an item (i.e. problem, cause, effect, measure or action) will occur to be estimated. Therefore, it will be necessary to define of the probability (value) at which we will accept or reject some information. This value should be set based on the experience of the experts of the domain.

$$P\,(\%) = \frac{\dfrac{\sum_{i=1}^{n} Historical\ \ cases}{n} + \dfrac{\sum_{j=1}^{m} Expert\ \ experience\,s}{m} + \dfrac{\sum_{k=1}^{p} EDSS\ \ proposals}{p}}{3} * 100$$

Equation-2

Where:

P: Probability in which a specific result (i.e. a problem diagnosis) can be found in historical cases, expert experiences and EDSS proposals.

Historical cases: Number of historical cases that experienced the result studied.

n: Number of historical cases studied.

Expert experience: Number of experts considering the result studied to be right.

m: Number of experts interviewed.

EDSS proposals: Number of EDSS proposals including the result studied.

p: Number of proposals studied.

The results for the historical and the laboratory expert validation are presented in the following sections: 4.5.2.1. Laboratory validation with historical data and 4.5.2.2. Laboratory validation with experts.

4.5.2.1. Laboratory validation with historical data

The validation process with historical data can only be done for eleven HSCWs: two of the thirteen Catalan HSCWs (*Riudecanyes* and *Sant Martí Sesgueïoles*) were not considered because the operation and maintenance protocols of these facilities were not available. However, the main adversity was the ill-defined operation and maintenance protocols provided by the technicians of the eleven facilities: these guidelines were poorly structured and scarcely detailed. Therefore, the protocols provided by EDSS-maintenance were compared to unsuitable statements and this comparison could only be done at two levels: problems and measures required to identify these problems.

- **Problems:**
  - EDSS-maintenance identified 17 potential problems (Table 4.8). Rules for problem {P1} - Abnormal vegetation growth during the start-up were not fired because all facilities are more than one year old.

Table 4.8. Comparison of the problems identified by EDSS-maintenance and the problems identified by the HSCW technicians.

	P 2	P 3	P 4	P 5	P 6	P 7	P 8	P 9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18
Alfés	red	yellow	red	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	red
Almatret Nord	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	red
Almatret Sud	yellow	yellow	red	yellow	yellow	yellow	yellow	red	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	red
Arnes	yellow	yellow	red	yellow	yellow	yellow	yellow	red	yellow	red	yellow	yellow	green	green	yellow	yellow	yellow
Cervià de Ter	yellow	red	red	red	yellow	yellow	red	red	yellow	red	yellow	red	green	yellow	red	yellow	yellow
Corbins	red	yellow	red	yellow	yellow	red	red	red	yellow	red	yellow	red	yellow	yellow	yellow	yellow	red
Gualba	yellow	red	red	yellow	yellow	yellow	yellow	red	yellow	red	yellow	yellow	green	yellow	red	red	red
La Fatarella	red	yellow	red	yellow	yellow	yellow	red	red	yellow	red	yellow	red	green	yellow	yellow	red	red
Verdú	yellow	yellow	red	yellow	yellow	yellow	red	red	yellow	red	yellow	yellow	green	yellow	yellow	yellow	yellow
Vilajuïga	yellow	yellow	yellow	yellow	yellow	yellow	red	red	yellow	green	yellow	green	green	yellow	yellow	yellow	yellow
Vilaplana	red	yellow	red	yellow	yellow	yellow	red	red	yellow	red	yellow	red	green	yellow	red	yellow	yellow

Red: Problem identified by EDSS-maintenance and by the HSCW technicians
Yellow: Problem identified by EDSS-maintenance but not by the HSCW technicians
Green: Problem identified by neither EDSS-maintenance nor the HSCW technicians

  - EDSS-maintenance identified an average of 16 potential problems for each HSCW: The rules for problem {P11} – Inappropriate wastewater distribution and problem {P13} - Deficient waterproofing were not fired in the *Vilajuïga* HSCW because it is fed by neither a perforated tube nor a channel, and does not have a waterproofing liner. The rules for problem {P14} - Deficient dike structure were not fired in those facilities where the HSCWs are buried on the soil (green boxes in Table 4.8).
  - According to the operation and maintenance protocols provided by the technicians of the HSCWs, only twelve of the seventeen potential problems were occasionally identified in the facilities (red boxes in Table 4.8).
  - In two facilities (*Almatret Nord* and *Corbins*) technicians identified a problem not included in the list of the EDSS-maintenance prototype problems: white worms inside the stem of *Phragmites australis.* This problem was detected once in each facility and was easily solved because it occurred in autumn, just before the *Phragmites australis* was cut.
  - The application of Equation-1 confirmed the results shown in Table 4.8: EDSS-maintenance identifies more problems (188) than those identified by the technicians (60).

$$V\,(\%) = \left(\frac{\sum_{j=1}^{j=n} R_j \;\; EDSS}{\sum_{j=1}^{j=n} R_j \;\; real} \right) \cdot \; 100 = \left(\frac{176}{60} \right) \cdot 100 = 293.3\,\%$$

This huge difference can be partially explained by (1) the poor quality of the operation and maintenance protocols provided by the technicians and (2) the lack of know-how about HSCWs. In some on-site visits we observed some problems (i.e. growth of trees on dikes) which were not recognized by technicians and, as a consequence, were not included in the protocol.

Moreover, the difference observed between the two kinds of protocols might be higher (303.4%) because the identification of the white worm problem in two HSCWs compensated the poor identification of the problems proposed by EDSS-maintenance prototype. Considering this new problem, the capability of EDSS-maintenance to identify problems became worse because it provided additional useless information and it did not have the capacity to identify one of the disturbances.

- **Measures:**
  - EDSS-maintenance prototype recommended 19 measures to identify the seventeen problems (Table 4.9). The visual control {M1} -Verify the state of the vegetation during the start-up, was not fired because all facilities studied were more than one year old.

Table 4.9. Comparison of measures proposed by EDSS-maintenance and measures carried out by HSCW technicians.

	M 5	M 9	M 10	M 12	M 13	M 14	M 15	M 19	M 20	M 25	M 27	M 28	M 29	M 30	M 33	M 34	M 35	M 38	M 39
Alfés	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Red	Red	Red
Almatret Nord	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Red	Red	Red	Red	Red
Almatret Sud	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Red	Red	Red	Red	Red
Arnes	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Green	Green	Red	Red	Red
Cervià de Ter	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Green	Red	Red	Red	Red
Corbins	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Red	Red	Red	Red	Red
Gualba	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Green	Red	Red	Red	Red
La Fatarella	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Green	Red	Red	Red	Red
Verdú	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Green	Red	Red	Red	Red
Vilajuïga	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Green	Green	Green	Red	Red	Red	Red
Vilaplana	Yellow	Red	Red	Red	Red	Red	Red	Red	Green	Red	Red	Red	Green	Red	Green	Red	Red	Red	Red

Red: Measure proposed by EDSS-maintenance and done by the HSCW technicians
Yellow: Measure proposed by EDSS-maintenance but not done by the HSCW technicians
Green: Measure not proposed by EDSS-maintenance and not done by the HSCW technicians

  - The great majority of measures concerning simple visual controls or inspections were supposed to be carried out by the studied systems because, despite there not being a record of all these controls, when the technicians were interviewed about the disturbances that can be detected with these controls, they were able to answer whether these problems took place in their plants or not. Hence, these controls were done although they may have been done unconsciously and, for that reason, they were marked in red colour in Table 4.9.

- The rules for measures {M20}, {M28}, {M29}, {M30} and {M33} were not fired in certain HSCWs because of the characteristics of these facilities (green boxes in Table 4.9) (i.e. {M33} was not proposed in the *Alfés* HSCW because this facility is not protected by a fence).
- The {M5} - Measure the water level was recommended for all the facilities but was only done in two of them because the rest do not have a lysimeter (orange boxes in Table 4.9).
- In all facilities other controls besides those proposed by the EDSS are carried out. These measures are related to the wastewater (influent and effluent) quality. These extra measures are not done according to the characteristics of the HSCW but rather according to the company responsible for operating the facilities. The eleven HSCWs are operated by five different enterprises; therefore, the additional controls can be divided into five groups (Table 4.10).

Table 4.10. Influent and effluent controls carried out in the eleven HSCWs.

	Group 1	Group 2	Group 3	Group 4	Group 5
Influent controls		BOD_5 COD SS	BOD_5 COD SS	BOD_5 COD SS N_T Ammonium P_T Conductivity pH	BOD_5 COD SS
Effluent controls	BOD_5 COD SS Conductivity pH	BOD_5 COD SS	BOD_5 COD SS	BOD_5 COD SS N_T Ammonium P_T Conductivity pH	BOD_5 COD SS

Group 1: *Alfés*, *Almatret Nord*, *Almatret Sud*, *Corbins* and *Verdú*
Group 2: *Arnes* and *La Fatarella*
Group 3: *Cervià de Ter* and *Vilajuïga*
Group 4: *Gualba*
Group 5: *Vilaplana*

Taking into account that EDSS-maintenance recommends measuring the concentration of organic matter {M27 and M39} and suspended solids {M38} in the effluent, only a total of 33 measures were proposed to check the water quality in the eleven HSCWs. On the contrary, in the real protocols a total of 71 measures (both influent and effluent controls) are recorded.

- Equation-1 was then applied considering all these aspects. At first sight, EDSS-maintenance does not cover the expected results (V < 100%) but, analysing all the above points, it was possible to conclude that the controls performed by the HSCW operators are similar to the controls recommended by EDSS-maintenance except for those related to wastewater quality. In this sense, operators carry out more measures than is recommended by EDSS-maintenance.

$$V\ (\%) = \left(\frac{\sum_{j=1}^{j=n} R_j\ EDSS}{\sum_{j=1}^{j=n} R_j\ real} \right) \cdot\ 100 = \left(\frac{187}{225} \right) \cdot 100 = 83.1\,\%$$

- From the comparison of measures recommended by EDSS-maintenance and measures taken by HSCW operators, another aspect can be highlighted: the frequencies with which these controls are performed.

  The eleven HSCWs are located in municipalities with a very sensitive or sensitive receiving media. Therefore, EDSS-maintenance recommends going to the WWTP at least, once a day to check whether or not the following disturbances are found: {P7}, {P8}, {P9}, {P10}, {P11}, {P12} and {P16}. Table 4.9 shows that the measures required to identify these problems are done daily in only four facilities (*Arnes*, *Gualba*, *La Fatarella* and *Vilaplana*). In the remaining HSCWs, these controls are done only two to four times a week.

  Concerning the measurement of organic matter {M27 and M39} and suspended solid {M38} concentration in the effluent, EDSS-maintenance recommends weekly control if the receiving media is very sensitive and fortnightly if the receiving media is sensitive. The recommended frequency is only carried out in four out of the thirteen communities:

  - A weekly control in *Vilaplana*, located in a very sensitive area.
  - A fortnightly control in *Cervià de Ter*, *Gualba* and *Vilajuïga*, each located in a sensitive area.

  The rest of the facilities should increase the frequency with which these controls are performed.

- **Modes, effects, causes and actions:**

  - As previously introduced, some problems included in the knowledge base of EDSS-maintenance are not considered as disturbances in real facilities. Hence, some modes are poorly evaluated, and even labelled as false statements. For instance, sometimes {P4} - Growing of weeds is not considered as a real disturbance and, as a consequence, the mode is considered false.
  - The effects detailed in the HSCW interviews are focused on those events with consequences for the neighbouring community: bad smells and the presence of mosquitoes.
  - No efforts were made to identify causes leading to problems. Once a problem appears, technicians apply a “general” corrective action. For example, confronted with the presence of rodents {P7}, operators usually trap these animals {AC21} without paying attention to whether or not there are remains of food that could be attracting rodents {C19}.
  - Actions done in the HSCWs aim to:
    - Improve the water distribution through the matrix (i.e. clean the tub {AC32} or the channel {AC34} that distributes wastewater, improve the wastewater distribution system {AC33 and AC35}, put coarse gravel in the inlet area {AC27} and remove solids accumulated over the matrix {AC25}).
    - Maintain the water flow under the matrix surface (i.e. decrease the water level {AC29} and use the reserve HSCW unit {AC30}).
    - Guarantee the health of *Phragmites australis* (i.e. cut the macrophytes at least once a year and remove weeds {AC7}).

4.5.2.2. Laboratory validation with experts

The stage of the laboratory validation involved three experts not connected to system development (Carlos Arias from the University of Aarhus, Joan García from the Technical University of Catalonia and Antonina

Torrens from the University of Barcelona). These HSCW experts checked the protocols provided by EDSS-maintenance prototype for 31 HSCWs located in the Fluvià River basin. These facilities are already planned but they have not been constructed, nor even designed yet. Therefore, input data from EDSS-maintenance related to the design features were invented. In reality, these data were not exactly invented because they were proposed considering the design of the Catalan HSCWs (i.e. since 50% of Catalan HSCWs are buried in the soil, 50% of the new HSCWs were also supposed to be buried in the soil). For this reason the 31 cases studied did not allow all the scenarios to be checked. Despite not being able to review all possible combinations, this laboratory validation allowed evaluation of all types of items included in the operation and maintenance protocols of HSCWs:

- **Problems and modes:**
  - EDSS-maintenance identified 537 potential problems for the 31 HSCWs studied. As can be deduced from Table 4.11, experts agreed with this prevision. Equation-1 corroborated this fact.

Table 4.11. Comparison of problems identified by EDSS-maintenance and problems identified by the HSCW experts.

	P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8	P 9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18
HSCW-1	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-2	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red	red	red
HSCW-3	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-4	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-5	red	red	red	red	red	red	red	red	red	red	red	green	red	green	red	red	red	red
HSCW-6	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-7	red	red	red	red	red	red	red	red	red	red	red	green	red	green	red	red	red	red
HSCW-8	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-9	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-10	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-11	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-12	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-13	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-14	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-15	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-16	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-17	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-18	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-19	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-20	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-21	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-22	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-23	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-24	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-25	red	red	red	red	red	red	red	red	red	red	red	green	red	green	red	red	red	red
HSCW-26	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-27	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red
HSCW-28	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-29	red	red	red	red	red	red	red	red	red	red	red	green	red	green	red	red	red	red
HSCW-30	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red
HSCW-31	red	red	red	red	red	red	red	red	red	red	red	red	red	green	red	red	red	red

(red) Problem identified by EDSS-maintenance and validated by the HSCW experts
(green) Problem not identified by EDSS-maintenance and not proposed by the HSCW experts

$$V\ (\%) = \left(\frac{\sum_{j=1}^{j=n} R_j\ EDSS}{\sum_{j=1}^{j=n} R_j\ real} \right) \cdot\ 100 = \left(\frac{537}{537} \right) \cdot 100 = 100\ \%$$

  - Experts also approved the definition of the 18 modes; hence the V value for this item is 100%.

- The positive evaluation of problems and modes by experts confirms the decision taken during the categorisation process which represented (1) the consideration of five problems as simple causes and (2) the categorisation of one problem as an effect (4.2.2.2. Categorisation).

- **Effects:**
  - All effects included in the EDSS-maintenance knowledge base appeared in the protocols. However, one of these effects was not successfully validated by the HSCW experts. The statement "The absence of fence or an inappropriate state of this structure can favour the presence of rodents" was considered false. According to the experts even if there is a fence, rodents can access the HSCW.
  - On the other hand, specialists on HSCW identified another potential effect: problems in wastewater distribution systems {P11} can favour matrix clogging {P8}.
  - The rejection of one effect and the addition of another raised the compensation phenomenon again. Hence, despite that EDSS-maintenance provided a wrong effect and omitted a correct one, the final V value was 100%.

- **Causes:**
  - According to the observations made in the effect items, one cause was neglected and another one was added: "The absence of fence or an inappropriate state of this structure can favour the presence of rodents" was not considered a cause of the presence of rodents {P7} while {P11} was regarded as a cause of matrix clogging {P8}.
  - Again, the compensation phenomenon appeared and despite EDSS-maintenance providing a wrong cause and omitting a correct one, the V value obtained was 100%.

- **Measures:**
  - The HSCWs are designed to remove a certain pollutant load (organic matter or suspended solids) per square meter and day. Initially, the EDSS-maintenance prototype recommended measuring organic matter {M27 and M39} and suspended solid {M38} concentration in the influent. Therefore, experts on HSCW recommended adding the measure of the influent flow {M3} to quantify the daily applied load and to verify whether or not there is overload of organic matter or suspended solids.
  - As a consequence of applying the measure of influent flow {M3} to identify the causes of organic matter {C1} or suspended solid {C20} overloading, the V value obtained was 97.3% because the EDSS-maintenance prototype did not recommend this measure.

$$V\,(\%) = \left(\frac{\sum_{j=1}^{j=n} R_j \ EDSS}{\sum_{j=1}^{j=n} R_j \ real} \right) \cdot 100 = \left(\frac{3938}{4046} \right) \cdot 100 = 97.3\,\%$$

  - As in the laboratory validation with historical data, the frequencies with which measures are carried out to identify problems were discussed. Experts on HSCWs argued that EDSS-maintenance prototype was too exigent. They proposed weekly rather than daily control.

- **Actions:**
  - Actions included in the EDSS-maintenance knowledge base were successfully validated. Only one action, “Planting through chicken wire fence fastened over the surface of the substrate to prevent animal from excavating tubes and rhizomes”, was discarded because of its cost and since experts on HSCWs believe that small rodents can overcome this constraint.
  - The application of Equation-1 confirms that the EDSS-maintenance prototype provided lightly few more actions than those considered applicable by HSCW technicians.

$$V\,(\%) = \left(\frac{\sum_{j=1}^{j=n} R_j \ EDSS}{\sum_{j=1}^{j=n} R_j \ real} \right) \cdot 100 = \left(\frac{7037}{7019} \right) \cdot 100 = 100.2\,\%$$

4.5.2.3. Knowledge base modifications

Some evidence of lack of knowledge and useless information was observed during the laboratory validation with historical data and experts. Hence, once these two partial validations were finished, an in-depth study was done to decide whether the knowledge base had to be modified or not. This study used Equation-2 to estimate the probability of items. When this probability was higher than 33.3% we decided on whether this item should be removed or included in the knowledge base or not. The 33.3% value was selected because it means that, at least in one of the three scenarios (historical cases, expert experiences and EDSS proposals), the item was successfully evaluated. In this study, the following aspects were analysed:

- **Lack of knowledge:**
  - In two HSCWs the presence of white worms inside the stems of *Phragmites australis* was detected. This problem was detected once in each facility but no reference has been found in the literature and interviewed experts had no knowledge of this problem. According to these observations, the probability of this new problem is around 6%. With this value, we decided not including this problem in the EDSS-maintenance knowledge base.

$$P_{white\ worms}\ (\%) = \frac{\frac{2}{11} + \frac{0}{31} + \frac{0}{42}}{3} * 100 = 6.1\%$$

  - All the facilities carry out more controls (Table 4.10) than those recommended by EDSS-maintenance to define wastewater quality (influent and effluent) (BDO_5, COD and suspended solid concentration in the effluent). These additional controls were divided into three groups according to the probability with which they are proposed or performed:

    1) BOD_5, COD and suspended solids concentration in the influent:

$$P_{BOD_5\ (\text{inf}),\ COD\ (\text{inf}),\ SS\ (\text{inf})}\ (\%) = \frac{\frac{6}{11} + \frac{0}{31} + \frac{0}{42}}{3} * 100 = 18.2\%$$

2) Total nitrogen, total phosphorus and ammonium concentration in the influent and effluent, and conductivity and pH in the influent:

$$P_{N_T\,(\inf\ and\ eff),\ P_T\,(\inf\ and\ eff),\ ammonium\,(\inf\ and\ eff),\ conductivity\,(\inf),\ pH\,(\inf)}\ (\%) = \frac{\frac{1}{11}+\frac{0}{31}+\frac{0}{42}}{3} * 100 = 3.0\%$$

3) Conductivity and pH in the effluent:

$$P_{conductivity\,(eff),\ pH\,(eff)}\ (\%) = \frac{\frac{2}{11}+\frac{0}{31}+\frac{0}{42}}{3} * 100 = 6.2\%$$

Controls of nitrogen, phosphorus, ammonium, conductivity and pH in both influent and effluent were not included in the knowledge base because their probability is lower than 6.2%. Despite the probability that controls of BOD_5, COD and suspended solid concentration in the influent is slightly higher, these controls were not included in the knowledge base because (1) they are expensive and (2) the final objective of the water quality controls is to verify whether or not HSCWs spill wastewater with less than X_i kg of $BOD_5/COD/SS \cdot m^{-3}$. Nevertheless, we do not discard including these controls in the knowledge base in the near future because the Council Directive 91/271/EC allows application of the reduction percentage instead of concentration values to control WWTP spills. In the reduction percentage case it will be necessary to measure BOD_5, COD and suspended solid concentrations in the influent.

- Experts on HSCWs considered that an unsuitable water distribution in the inlet {P11} could favour matrix clogging {P8}. This affirmation led to a review of operation and maintenance protocols of the eleven Catalan HSCWs. This revision led to the discovery of a correlation between {P11} and {P8}: in six HSCWs {P11} can be the origin of {P8}. From Equation-2 the probability of this correlation was estimated. This probability was superior to 50%, hence {P11} was included in the knowledge base as a cause of {P8}.

$$P_{BOD\,(\inf),\ COD\,(\inf),\ SS\,(\inf)}\ (\%) = \frac{\frac{6}{11}+\frac{31}{31}+\frac{0}{42}}{3} * 100 = 51.5\%$$

- To identify the causes of influent overload of organic matter {C1} and suspended solids {C20}, experts on HSCWs recommended measuring both the pollutant concentration and the flow rate. EDSS-maintenance prototype does not propose measuring the flow rate. Operators from the eleven Catalan HSCWs interviewed did not recommend this control either. With these aspects in mind, Equation-2 was applied. Considering the three scenarios (historical data, experts and decision support system), the probability of recommending both measures was found to be 33.3%. Therefore, the flow rate measure {M3} was included in the knowledge base as a measure to identify organic or suspended solid overload in the influent.

$$P_{BOD\,(\inf),\ COD\,(\inf),\ SS\,(\inf)}\ (\%) = \frac{\frac{0}{11}+\frac{31}{31}+\frac{0}{42}}{3} * 100 = 33.3\%$$

- **Useless knowledge:**
  - From the laboratory validation with historical data it might seem that EDSS-maintenance prototype does not correctly identify the problems because some problems identified {P6, P10 and P12} did not appear in any of the eleven real protocols. Even in these cases, the successful validation of experts rejected this negative hypothesis. The application of Equation-2 to {P6}, {P10} and {P12} confirmed that these problems were identified in almost 67% of the situations, hence it justified changing nothing in the EDSS-maintenance knowledge base.

$$P_{\{P6\},\,\{P10\},\,\{P12\}}\ (\%) = \frac{\frac{0}{11}+\frac{31}{31}+\frac{42}{42}}{3} * 100 = 66.7\%$$

  - Experts on HSCWs considered that a fence cannot avoid the presence of rodents. Hence the statement "The absence of a fence or an inappropriate state of this structure favour the presence of rodents" was considered neither a cause of problem {P7} nor an effect of problem {P15}. Moreover, this affirmation led to a review of the operation and maintenance protocols of the eleven Catalan HSCWs. This revision led to the discovery that the HSCW which had problems with rodents is protected by a fence. Equation-2 confirms that this statement was only considered true in the operation and maintenance protocols provided by the EDSS-maintenance prototype. For this reason, this statement was removed from the knowledge base.

$$P\ (\%) = \frac{\frac{0}{11}+\frac{0}{31}+\frac{42}{42}}{3} * 100 = 33.3\%$$

  - Experts on HSCW rejected the action of planting through chicken wire fence fastened over the surface of the substrate to prevent animals from excavating tubes and rhizomes. Furthermore, no successful applications of this action had been found in the laboratory validation with historical data. Therefore, this action was removed from the EDSS-maintenance knowledge base. Equation-2 confirms this decision.

$$P\ (\%) = \frac{\frac{0}{11}+\frac{0}{31}+\frac{42}{42}}{3} * 100 = 33.3\%$$

- **Observation:** In both laboratory validation steps, the frequencies with which measures have to be performed were discussed. In this sense, no changes were made to the knowledge base because:
  - The eleven HSCW technicians interviewed had performed 35% of the measures with the same frequency recommended by EDSS-maintenance.
  - The literature revision carried out confirmed the rate of occurrence of these controls.

4.5.2.4. Future validation work: The field validation

Field validation will consist of applying the operation and maintenance protocols provided by EDSS-maintenance in (a) HSCWs that are currently operating and (b) HSCWs that will be constructed before 2015. This field testing will be carried out in the near future and, since the EDSS-maintenance prototype has been built with a single model, it will be focused on:

- Assuring that the EDSS-maintenance prototype can deal with real qualitative and quantitative variables and missing information and detecting weak reasoning.
- Evaluating the usability of protocols provided by the EDSS-maintenance prototype in both senses:
  - Objectively and quantitatively by means of functioning errors and productivity.
  - Subjectively through user preferences and interface characteristics.
- Evaluating the usefulness comparing both situations with and without the protocols provided by the EDSS-maintenance prototype.

4.5.3. Recommendations to build the full EDSS-maintenance

The evaluation process of an EDSS is still an open problem and no clear strategies are yet well established for facing on of the more critical phases of the development of an EDSS [Sànchez-Marrè *et al.* (2006)]. To evaluated the full EDSS-maintenance we proposed methodology based on four steps (Figure 4.88): (1) verification, (2) laboratory validation with historical data, (3) laboratory validation with experts and (4) field validation (3.5. Evaluation process).

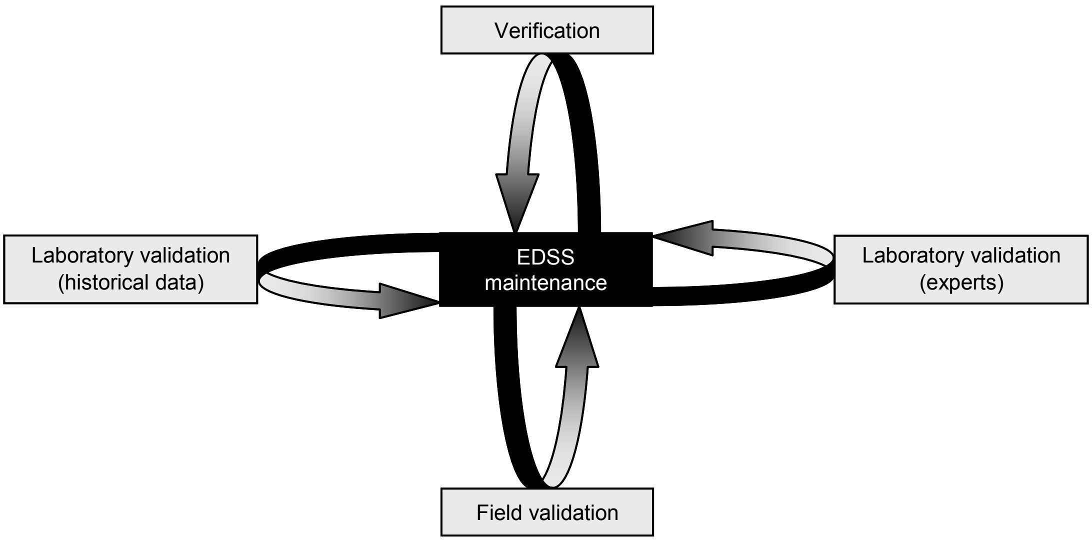

Figure 4.88. Methodology to evaluate EDSS-maintenance.

Each one of these steps has a certain complexity associated with it:

- The complexity of the verification process arouse from the impossibility of checking all the scenarios.
- The complexity of the laboratory validation with historical data was due to the quality of the operation and maintenance protocols provided by WWTP operators. Generally these protocols were poorly structured and scarcely detailed.
- The complexity of the laboratory validation with experts and the field validation is attributed to the subjectivity of the experts in the evaluation of the protocols.

To confront the complexity of the verification step it is crucial to define the scenarios to be tested in order to verify the completeness and consistency of the EDSS. The scenarios tested must covert the normal situations as well as some extreme or abnormal ones.

Regarding laboratory validation with historical data, we expect that the complexity associated with this evaluation step can be managed with the information obtained from the recommended field studies to improve the quantity and quality of the monitoring, operation and maintenance knowledge obtained from the questionnaires and the onsite studies.

The last point of complexity, the subjectivity of experts, may never be solved but EDSS-maintenance can probably contribute to decreasing the degree of complexity because it incorporates expert knowledge and, consequently, facilitates the sharing and rapid re-use of technical knowledge and experiences among plant managers.

To quantify how *good* the EDSS-maintenance is we proposed using Equation-1 which compares the results provided by the EDSS-maintenance with the “reality” (historical data and experts). Moreover, to assess whether or not the knowledge base has to be modified, we proposed using Equation-2 which considers the probability that a result provided by the EDSS can be found in (1) historical cases, (2) expert experiences and (3) the EDSS proposals.

5. EDSS-maintenance prototype operation

5. EDSS-maintenance prototype operation

The steps followed during the operation of the EDSS-maintenance prototype to provide the most adequate operation and maintenance recommendations for a given HSCW, are: 5.1. Data gathering, 5.2. Diagnosis and 5.3. Decision support (Figure 5.1).

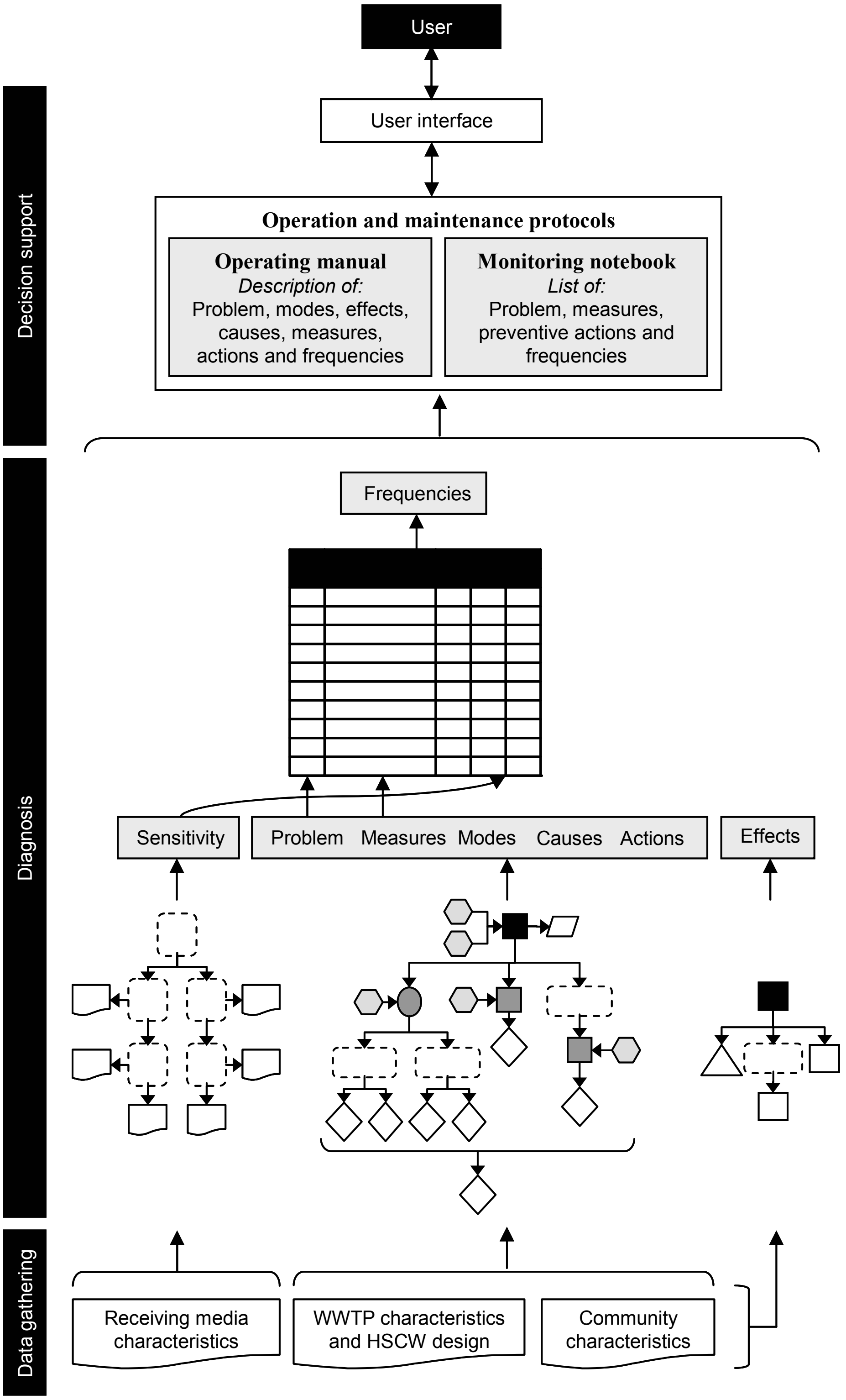

Figure 5.1. The operation of the EDSS-maintenance prototype.

5.1. Data gathering

The first stage in the EDSS-maintenance prototype operation encompasses the tasks involved in data gathering and recording into the working memory. For each HSCW, the user introduces data concerning: (a) the community characteristics, (b) the receiving media properties, (c) the treatment plant characteristics, and (d) the HSCW design (Table 5.1).

Table 5.1. Input data required to define the operation and maintenance protocols using the EDSS-maintenance prototype.

Community characteristics	• Community identification code • Community name • Region name • River basin name • Number of inhabitants • Number of seasonal inhabitants • Number of industries • Size of industries • Activity of industries
WWTP characteristics	• Altitude above sea level • Distance between the WWTP and the community • Distance between the WWTP and the receiving media • WWTP parcel surface * • Constructed parcel surface * • Presence of a fence * • Water sources * • Energy sources • Year of construction • Year of operation startup * • Pre-treatment • Primary treatment • Secondary treatment • Tertiary treatment
HSCW design	• Number of HSCW basin • Basin sizes: width, length and depth • Bottom slope • Dike slope: internal and external * • Dike material * • Dike protection * • Waterproofing * • Matrix: gravel diameter and gravel distribution * • Wastewater distribution system * • Wastewater collection system • By pass * • Recirculation * • Mechanism to dose wastewater * • Mechanism to control the water level * • Macrophyte species planted • System of plantation • Density of plantation * • Year of plantation *
Receiving media characteristics	• Months over a year that water flows into the receiving media * • Nitrate polluted area * • Specific protected area * • Presence of aquifers * • Presence of natural ponds * • Presence of fishing areas * • Presence of bathing areas

* Input data required to define the monitoring notebook and the operating manual (5.3. Decision support).

Data required to define the operation and maintenance protocols for HSCWs are introduced into the working memory through four different user-interfaces (one per each block of data). These interfaces make EDSS-maintenance a user-friendly application because they allow: (a) the easy introduction of input data and (b) the possibility to save and retrieve this information. Figure 5.2 shows the EDSS-maintenance interface to introduce the input data for the community characteristics (in Catalan).

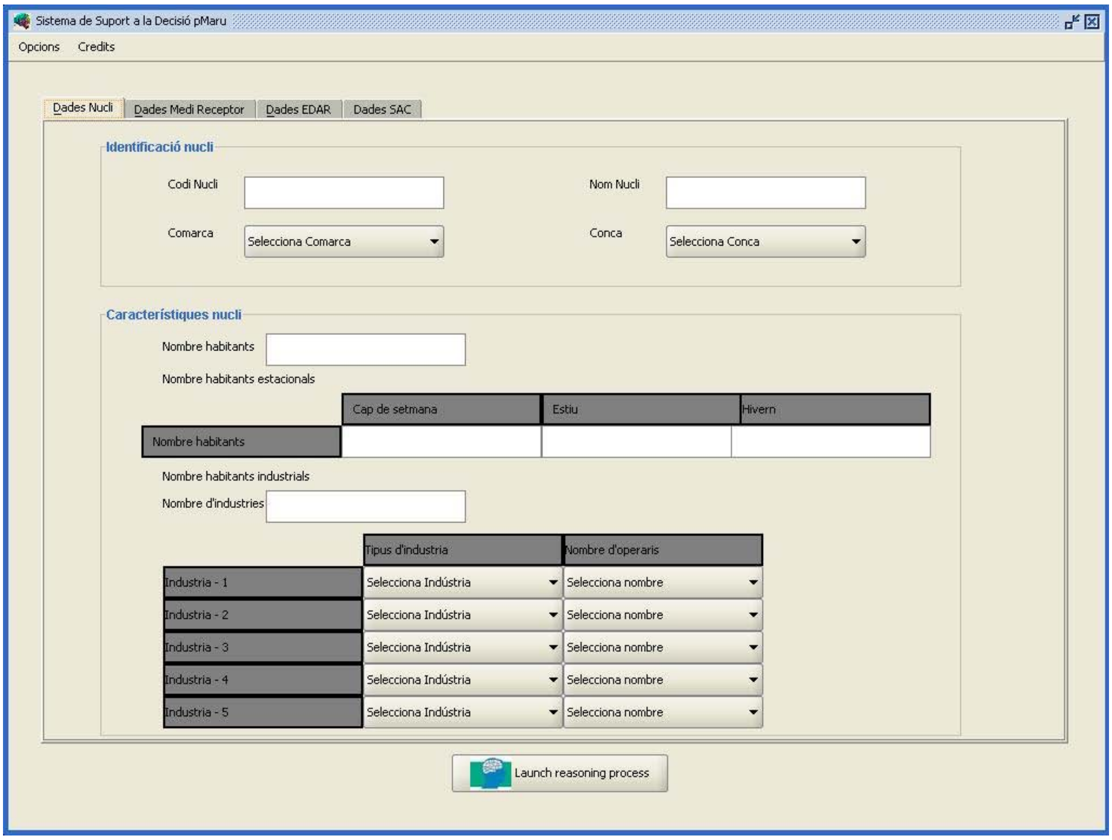

Figure 5.2. EDSS-maintenance user-interface to introduce the community characteristics (in Catalan).

Original raw data is often defective, requiring a number of pre-processing procedures before they can be recorded in an understandable and interpretable way [Poch *et al.* (2004)]. There is a software module (*CheckInput.java module*) that allows the numeric input data to be properly checked before being recorded in the data base (i.e. if the value has to be a whole number the Java module does not allow decimal points, if the value has to be a decimal the Java module does not allow a decimal expressed in hundredths, if the cell has to be filled with a text the Java module does not allow a number).

Moreover, if some of the data required to define the monitoring notebook and the operating manual (Table 5.1) is omitted, the EDSS-maintenance prototype advises the user that there is a missing data.

5.2. Diagnosis

The second step of the EDSS-maintenance operation, diagnosis, includes the reasoning procedure that is used to infer the state of the process so that a reasonable proposal for the operation and maintenance protocols can be given. This reasoning process has already been presented in Figure 4.30 and is described in more detail in Figure 5.1:

- From the characteristics of the community, the WWTP and the HSCW design, EDSS-maintenance identifies the causes of failures, the problems themselves, the measures to detect problems and causes, and any preventive and/or corrective actions.
- From the characteristics of the receiving environment, EDSS-maintenance defines its sensitivity.
- From the intermediate results (problems, measures, preventive actions and sensitivity), EDSS-maintenance recommends the frequencies with which the measures and preventive actions must be taken.
- Finally, from the whole set of the input data, EDSS-maintenance identifies the effects on the receiving media.

This procedure is accomplished with the help of the RBS.

5.3. Decision support

The decision support step establishes a supervisory task that gathers and merges the conclusions derived from the knowledge-based system [Poch *et al.* (2004)]. Problems, modes, effects, causes, measures and actions inferred from the reasoning procedure of the EDSS-maintenance prototype are summarized and organized into two documents:

- **Monitoring notebook:** The monitoring notebook includes the list of measurements needed to define the state of performance and the recommended preventive action for a specific HSCW. These two lists are provided in tables and organised according to the frequencies with which the controls and actions must be carried out. The monitoring notebook has to be filled with the following information: i) the date and time when monitoring activities are carried out; ii) the person responsible; iii) the measurement results obtained; and iv) the problems encountered and the corrective actions applied (in the 'Observations' field) (5.4.2. Monitoring notebook).
- **Operating manual:** The operating manual document provided by the EDSS-maintenance prototype for every HSCW has two objectives: (1) to explain in detail the required measurements and the preventive actions specified in the monitoring notebook and (2) to describe the procedure to be followed once a problem appears. This second objective involves (2_a) identifying the causes behind the disturbances and (2_b) applying the most appropriate actions. To attain these objectives, the operating manual document defines the modes, the causes, the monitoring programme, the preventive and corrective actions and the effects for each situation of potential failure identified for a given HSCW (5.4.3. Operating manual).

Despite these two documents being the core of the operation and maintenance protocols (documents 4 and 5 in Figure 5.3), these guidelines also include:

- **Operation and maintenance protocol presentation** (document 1 in Figure 5.3): This document offers a simple presentation of the operation and maintenance protocols, (1) describing the documents composing these guidelines and (2) providing some advice on how to use the protocols.
- **Horizontal subsurface constructed wetland description** (document 2 in Figure 5.3): To facilitate the comprehension of recommendations given by the operation and maintenance protocols, there is a description of HSCW technology in terms of components, processes, advantages and limitations.

– **HSCW characteristics** (document 3 in Figure 5.3): Monitoring and operating manuals are defined according to the characteristics of each HSCW system. Thus, it seems appropriate to provide the features involved in defining the operating and maintenance manuals as an additional outcome of EDSS-maintenance.

The final protocol is sent through the computer interfaces to the user. The user can choose to view, save and print out a single document or the full protocol (the five documents). Figure 5.3 shows the user interface of EDSS-maintenance that summarises the protocol proposal for a given HSCW (*Hostalnou de Bianya*).

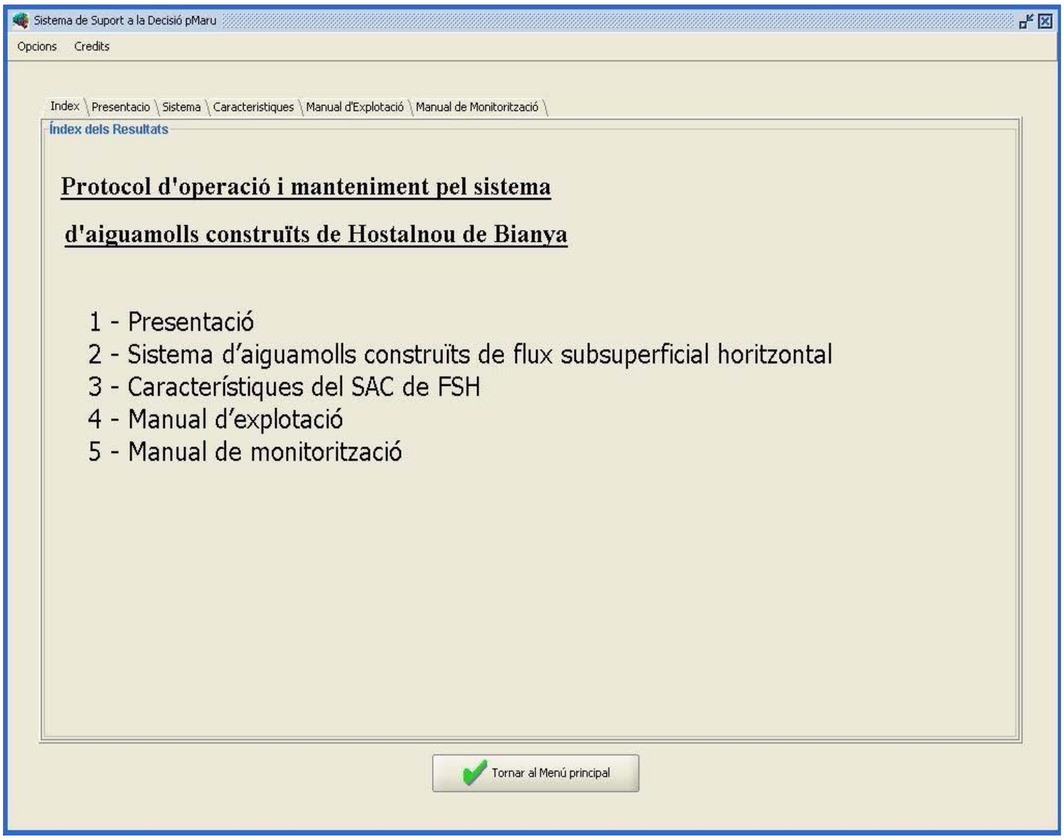

Figure 5.3. User-interface showing a summary of the results the EDSS-maintenance proposal for a given HSCW (*Hostalnou de Bianya)* (in Catalan).

5.4. Example of an operation and maintenance protocol provided by the EDSS-maintenance prototype

Next, to conclude the presentation of the EDSS-maintenance prototype and to illustrate its capabilities, an example of an operation and maintenance protocol provided by the system is given. This case study presents the operation and maintenance recommendations for the *Hostalnou de Bianya* HSCW. Subsequent subsections present the variables used to define the protocol (5.4.1. Characteristics of the HSCW), the monitoring recommendations made by EDSS-maintenance (5.4.2. Monitoring notebook) and a summary of the operation and maintenance requirement definitions (5.4.3. Operating manual). For further details in the LEQUIA (2006) report there is an entire protocol (in Catalan).

5.4.1. Characteristics of the HSCW

For every HSCW, the user must introduce data about: (a) the characteristics of the community where the facility is located, (b) the properties of the receiving media, (c) the characteristics of the treatment plant, and (d) the design parameters of the HSCW treatment unit. Table 5.3 lists the input data concerning the characteristics of *Hostalnou de Bianya*, a small community located at the North-East of Catalonia, with a fixed population of 75 inhabitants and without any industries spilling wastewater into the sewer.

The *Hostalnou de Bianya* WWTP is located close to the community, on a large site surrounded by a fence. This area is easily accessible but it does not have a potable water source or electricity. This WWTP consists of a thick-fine screen as pre-treatment, a septic tank as primary treatment and a constructed wetland as secondary treatment. There is not any tertiary treatment because only secondary treatment (organic matter and suspended solids) is required.

The constructed wetland is a HSCW unit of 600 m^2, dug into the ground and filled with medium gravel in the inlet and outlet areas and fine gravel in the middle. The gravel is planted with *Phragmites australis*. Wastewater is distributed along the entrance with a perforated tube and it is gathered by a perforated tube. This collection tube is located at the bottom of the outlet area of the basin and it is connected to a mechanism that can vary the water level. To avoid any filtration of wastewater into the soil, and the infiltration of water from the soil into the HSCW, the basin is waterproofed with a synthetic membrane.

The *Hostalnou de Bianya* WWTP is located in neither a nitrate-polluted nor a specific-protected area. Around the site there are not any natural ponds or aquifers. The receiving media has a seasonal flow, and does not have areas for fishing and bathing.

All these characteristics (community, WWTP, HSCW and receiving media) are summarized in Table 5.2. Part of these data was obtained from the EDSS-treatment databases, and the rest (data in italics) was invented based on (1) our experience and (2) the objective of this case study (illustrate the capabilities of EDSS-maintenance).

These data was introduced into EDSS-maintenance through the input data user-interfaces presented in 5.1. Data gathering (i.e. Figure 5.2).

5.4.2. Monitoring notebook

From the community characteristics, the WWTP characteristics and the design parameters of the *Hostalnou de Bianya* HSCW, EDSS-maintenance identified 17 potential problems and suggested carrying out the following controls to detect these problems: {M1}, {M5}, {M9}, {M10}, {M12}, {M13}, {M14}, {M15}, {M19}, {M20}, {M25}, {M27}, {M28}, {M30}, {M34}, {M35}, {M38}, and {M39}. In addition, EDSS-maintenance recommended preventive action {AC56} (Table 5.3).

From the receiving media characteristics, EDSS-maintenance fixed the sensitivity of the spill point: resistant. According to this category, EDSS-maintenance recommended the frequencies of the controls (Table 5.3). In this case almost all the controls have to be done weekly. Only {M12}, {M27}, {M38} and {M39} have to be done monthly.

Table 5.2. List of input data used to define the operation and maintenance protocol for *Hostalnou de Bianya*.

Community characteristics	Community identification code	3288-01-01
	Community name	Hostalnou de Bianya
	Region name	La Garrotxa
	River basin name	El Fluvià
	Number of inhabitants	75
	Number of seasonal inhabitants	0
	Number of industries	0
	Size of industries	/
	Activity of industries	/
WWTP characteristics	Altitude above sea level	480 m
	Distance between the WWTP and the community	169 m
	Distance between the WWTP and the receiving media	2 m
	WWTP parcel surface	10.000 m^2
	Constructed parcel surface	*1.200* m^2
	Presence of a fence	*Yes*
	Water sources	No (potable water at 225 m)
	Energy sources	No (electricity at 225 m)
	Year of construction	*2007*
	Year of operation startup	*2007*
	Pre-treatment	Thick-fine screen
	Primary treatment	Septic tank
	Secondary treatment	HSCW
	Tertiary treatment	/
HSCW design	Number of HSCW basin	*1 unit*
	Basin sizes: width, length and depth	*12 m, 50 m and 0,6 m*
	Bottom slope	*1 %*
	Dike slope: internal and external	*50 % and 0 %*
	Dike material	*Soil*
	Dike protection	*No*
	Waterproofing	*Yes (membrane + UV membrane)*
	Matrix: gravel diameter and gravel distribution	*Inlet - outlet:* D_{10} *= 32 mm and 1,5 m* *Centre:* D_{10} *= 16 mm and 47 m*
	Wastewater distribution system	*Tube*
	Wastewater collection system	*Perforated tube*
	By pass	*No*
	Recirculation	*No*
	Mechanism to dose wastewater	*No*
	Mechanism to control the water level	*Yes*
	Macrophyte species planted	*Phragmites australis*
	System of plantation	*Plants*
	Density of plantation	*4 plants/*m^2
	Year of plantation	*2007*
Receiving media characteristics	Months a year that water flows into the receiving media	11 months
	Nitrate polluted area	No
	Specific protected area	No
	Presence of aquifers	No
	Presence of natural ponds	No
	Presence of fishing areas	No
	Presence of bathing areas	No

Table 5.3. List of the controls, the preventive action and the frequencies of both, recommended for *Hostalnou de Bianya* HSCW.

Problem	Measure	Control Frequency *[1]
P1	M1: Visual control of vegetation to verify the growth of *Phragmites australis*	W
P2	M13: Visual control of vegetation to verify the density and homogeneity of *Phragmites australis*	W
P3	M9: Visual control of HSCW surface to verify the accumulation of vegetation remains	W
P4	M10: Visual control of HSCW surface to verify the growth of weeds	W *[2]
P5	M12: Visual control of HSCW surface and surroundings to verify the growth of trees and bulrushes	M
P6	M14: Visual control of vegetation to verify the colour of *Phragmites australis*	W
P7	M15: Visual control of HSCW and surroundings to verify the presence of rodents	W
P8	M19: Visual control of HSCW to verify matrix clogging	W
P9	M5: Measure the water level in HSCW M25: Visual control of HSCW to verify water flow over the matrix	W
P10	M5: Measure the water level in HSCW	W
P11	M28: Visual control of tubes to verify the accumulation of solids	W
P12	M20: Visual control of the water level controller to verify its state and regulation	W
P13	M30: Visual control of waterproofing to verify its state	W
P15	M34: Visual control of fence and gate to verify their state	W
P16	M35: Visit to facilities to verify formation of bad smells	W
P17	M27: Measure the concentration of organic matter (BOD_5) of the effluent M39: Measure the concentration of organic matter (COD) of the effluent	M
P18	M38: Measure the concentration of suspended solids (SS) of the effluent	M
P_i *[3]	AC56: Cut the macrophytes	Y

*[1] W: Weekly, M: monthly; Y: yearly.
*[2] Weekly in springtime, fortnightly in summer and autumn, monthly in winter.
*[3] Y: Yearly.

Figure 5.4 shows the EDSS-maintenance interface that provides the monitoring notebook for the *Hostalnou de Bianya* HSCW. In this case study, all the controls are grouped in a single table that must be filled weekly. At the bottom of this table it is indicated that four of the controls from the list must be performed monthly instead of weekly, and it is also stated that the preventive action {AC56} must be taken, at least, once a year.

Since the EDSS-maintenance protocols are adapted to the characteristics of each facility, the list of measures varies among HSCWs. The following examples illustrate the dependency of the operation and maintenance protocols on the wastewater treatment system characteristics, and justify part of the contents of the monitoring notebook for *Hostalnou de Bianya*:

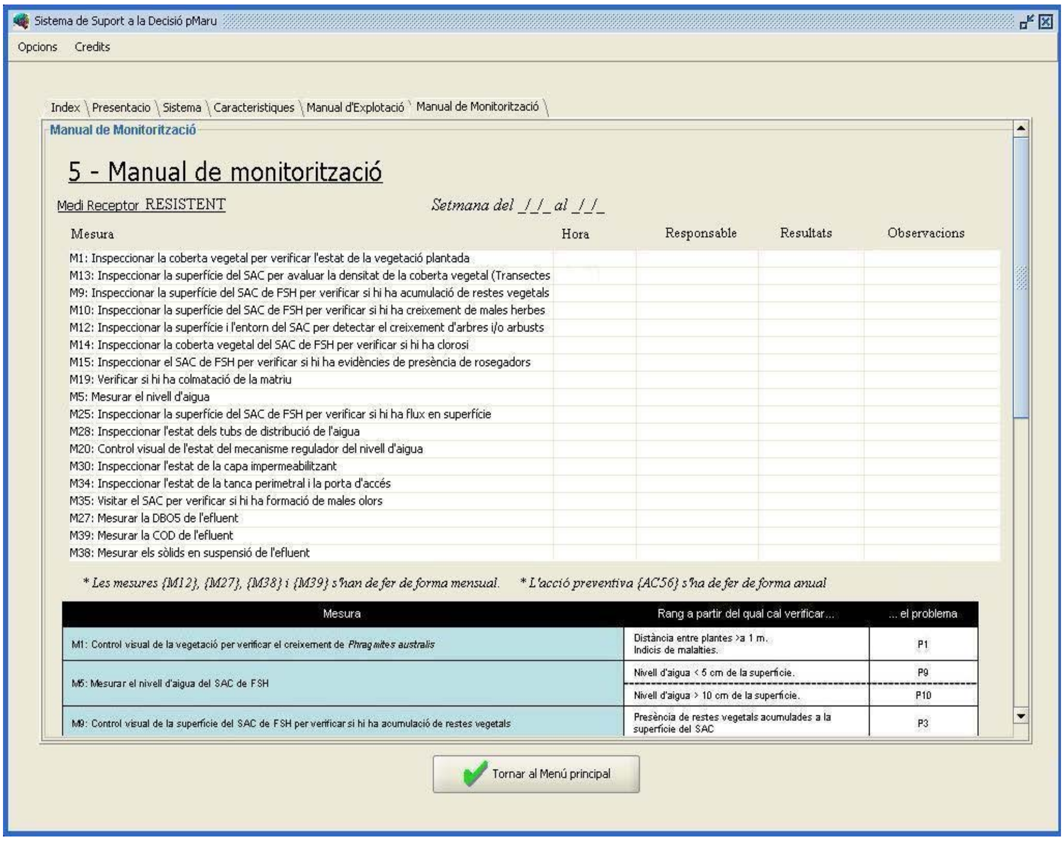

Figure 5.4. The EDSS-maintenance interface for the monitoring notebook (in Catalan).

- If the HSCW is new or less than one year old, problem {P1} - Abnormal vegetation growth will appear on the list of problems and, as a consequence, measure {M1} - Visual control of vegetation to verify growing of *Phragmites australis* will be included in the monitoring notebook. On the other hand, if the HSCW is more than one year old, problem {P1} and measure {M1} will not be considered in the operation and maintenance protocol (Figure 5.5.A).

- If the HSCW has a mechanism to control the water level in the gravel beds, {P12} - Inappropriate water level controller regulation or maintenance can be a problem and, therefore, measure {M20} - Visual control of the water level controller to verify its state and regulation will be included in the monitoring notebook. However, if the facility does not have a water-level controller, {P12} will not be included in the list of problems, while the preventive action {AC54} - Install a water-level controller will be recommended instead (Figure 5.5.B).

- If the HSCW dikes are built with compacted soil, then problem {P14} – Deficient dike structure will be considered in the protocol. However, if the dikes are made with concrete or the HSCW is built into the ground, problem {P14} will not be identified, hence, control {M33} - Visual control of dikes to verify their state will not be included in the monitoring notebook (Figure 5.5.C).

- If the HSCW is fed by means of a perforated tube, then EDSS-maintenance will include control {M28} - Visual control of tubes to verify the accumulation of solids in the operation and maintenance protocol, but if wastewater is distributed through a channel, then control {M29} - Visual control of channels to verify the accumulation of solids will be recommended (Figure 5.5.D).

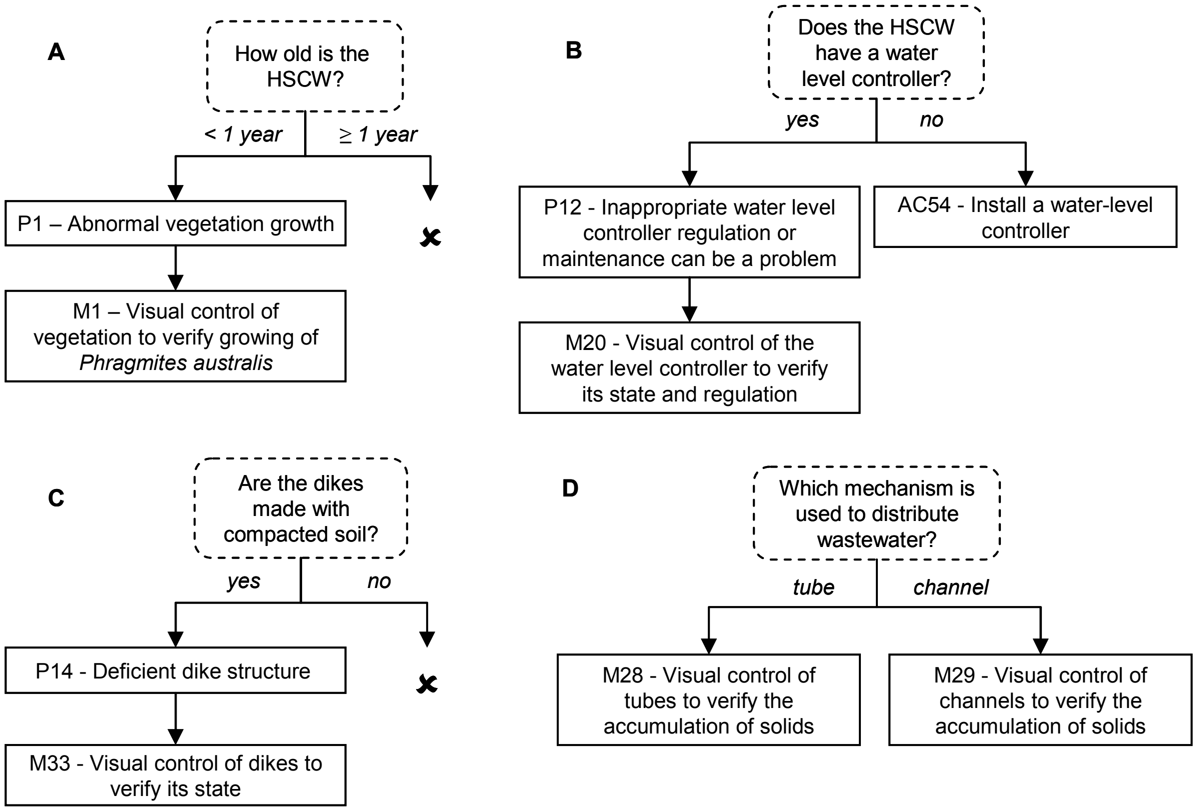

Figure 5.5. Flow diagram with the reasoning paths for: A) the age of the HSCW, B) the water level controller, C) the dikes and D) the wastewater distribution system.

Although in most of the cases the frequencies of measurements depend on the sensitivity of the receiving media, there are a few exceptions where the frequency is independent of that sensitivity because of the associated environmental effects. For instance, while the visual controls to check the state of the water distribution system {M28 and M29} are carried out on a daily basis if the receiving media is very sensitive or sensitive and weekly if the environment is resistant, the visual control to check the state of the fence {M34} is performed weekly in all cases. The state of the water distribution system is crucial to maintaining the environmental impact on the receiving media low, while the state of the fence is not.

The monitoring notebook will vary among HSCWs whenever there are changes in (1) the list of potential problems, (2) the required measures to identify these disturbances or (3) the frequencies of these controls. The changes observed in the monitoring notebook can be both (1) the number of measures in a table and (2) the number of tables (i.e. when the receiving media is resistant there is only one table (Figure 5.4), but when it is very sensitive or sensitive a new table containing daily controls appears).

Whatever the characteristics of the facility and the sensitivity of the receiving media, the preventive action {AC56} must be done yearly.

5.4.3. Operating manual

The operating manual for the HSCW of *Hostalnou de Bianya* describes the seventeen potential problems identified by EDSS-maintenance. For every disturbance EDSS-maintenance defines the modes, the causes, the monitoring program (measures to identify problems and measures to identify causes), the preventive and corrective actions and the effects for each situation of potential failure. This information is organized in technical cards (one per problem) as follows (Table 5.4):

- Technical card title: Problem
- Problem definition: Mode
- Problem effects: List and definition of the effects
- Measures to identify the problem: List and description of the measures to identify problems and their recommended frequencies
- Action plan: List and description of the causes of the problems, list and description of the measures to identify the causes and list of the corrective actions.

The corrective actions are described on another technical card once all the problems have been described. Hence, the operating manual for the HSCW of *Hostalnou de Bianya* includes eighteen technical cards, one for each potential problem and one describing the corrective actions.

Table 5.4. Technical card for problem {P1} – Abnormal vegetation growth.

TECHNICAL CARD
P1: Abnormal vegetation growth during the start-up.
Problem definition
MD1: Deficient growth of *Phragmites australis* during the vegetation establishment phase.
Problem effects
P2 – Low density or non-homogeneous density of vegetation: The abnormal growth of *Phragmites australis* can favour a low density or a non-homogeneous density of vegetation. **P4 – Growth of weeds in the HSCW area:** The abnormal growth of *Phragmites australis* can favour the growth of weeds. **P17 – High concentration of organic matter in the effluent:** The abnormal growth of *Phragmites australis* can cause an increase in the concentration of organic matter in the effluent. **P18 – High concentration of suspended solids in the effluent:** The abnormal growth of *Phragmites australis* can cause an increase in the concentration of suspended solids in the effluent.
Measures to identify the problem
M1 – Visual control of the vegetation to verify the state of the planted macrophytes: Inspect the vegetation of the HSCW to verify whether *Phragmites australis* growth is homogeneous, the density of plants is higher than 4 plants per square meter, there are diseases, etc. **Frequency:** Weekly
Action plan to solve the problem
Once the problem is identified, identifying the cause of the dysfunction is recommended to apply the most appropriate corrective action. ***CAUSE:*** **C1 – Organic overload:** An organic overload can have repercussions on the proper growth of the planted vegetation.

Table 5.4 (continuation). Technical card of problem {P1} – Abnormal vegetation growth.

MEASURE:

M2 – Measure the concentration of organic matter (BOD_5) in the influent: Measure the BOD_5 of the influent according to the Standard Method guidelines.

M3 – Measure the influent flow rate: Measure the influent flow rate of the HSCW. If is not possible, measure the flow rate at the WWTP.

ACTION:

AC3 – Reduction of the organic load: Previous treatment

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC51 – Provide a source of clean water

AC52 – Install a recirculation device

CAUSE:

C2 – Low temperatures: The minimum temperature which *Phragmites australis* can tolerate is 6ºC. Below this temperature the plants enter into a state of latency, a state in which growth slows down or is completely stopped until temperatures become favourable. If the temperatures fall below 0 ºC the risk of mortality to *Phragmites australis* increases.

MESURE:

M4 – Measure the temperature: Measure the temperature of the air with a thermometer. If the measurement cannot be taken, qualitative types of observations are accepted (i.e. solar radiation, intense light, occasional clouds, partly cloudy or cloudy).

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

CAUSE:

C3 – High temperatures: The maximum temperature tolerated by *Phragmites australis* is 26ºC. Above this temperature the vegetation growth is limited, and in extreme cases it may produce the death of the plants.

MESURE:

M4 – Measure the temperature: Measure the temperature of the air with a thermometer. If the measurement cannot be taken, qualitative types of observations are accepted (i.e. solar radiation, intense light, occasional clouds, partially cloudy or cloudy).

M5 – Measure the water level: Measure the water level inside the cells using of a lysimeter.

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC31 – Increasing the water level

Table 5.4 (continuation). Technical card of problem {P1} – Abnormal vegetation growth.

CAUSE:

C4 – High evapotranspiration: High evapotranspiration can limit the growth of the vegetation planted and may cause the death of the plants.

MEASURE:

M5 – Measure the water level: Measure the water level inside the cells using a lysimeter.

M6 – Measure the evapotranspiration: Evapotranspiration can be estimated from solar radiation and the wind; it may also be measured with an evaporimeter.

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC31 – Increasing the water level

CAUSE:

C5 – Heavy rainfall: Heavy rainfall or long periods of rain may influence the correct growth of the vegetation planted.

MEASURE:

M5 – Measure the water level: Measure the water level inside the cells using a lysimeter.

M7 – Measure the rainfall: Measure the precipitation with a pluviometer. If this equipment is not available, qualitative type measurements are recommended (i.e. the intensity – zero, light rain, moderate rain, heavy rain, snow or hail – and the duration of the precipitation).

M25 – Visual control of the HSCW surface to verify whether there is wastewater flow over the matrix: Visual control of the HSCW surface to verify whether there is wastewater flow over the matrix.

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC29 – Decreasing the water level

CAUSE:

C6 – Strong gusts of wind: Strong gusts of wind may bend and damage the vegetation of the HSCWs.

MEASURE:

M8 – Measure the wind (intensity and direction): Measure the intensity and direction of wind with an anemometer. Where this equipment is not available, qualitative type measurements are recommended (i.e. direction – north, south, east or west – and intensity – calm, breeze, moderate wind and strong wind –).

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC45 – Planting a tree screen

Table 5.4 (continuation). Technical card of problem {P1} – Abnormal vegetation growth.

CAUSE:

P4 – Growth of weeds in the HSCW area: Weeds which grow in the HSCW area may compete with *Phragmites australis* for space and nutrients, making the required establishment and development of the plant difficult.

MEASURE:

M10 – Visual control of the HSCW surface to verify whether there is any growth of weeds: Visual control of the HSCW surface to verify whether there is any growth of weeds.

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC-P4 – Apply recommendations done in problem {P4}

CAUSE:

P5 – Growth of trees and/or bushes in the HSCW area and/or surrounding area: *Phragmites australis* is a plant which needs sun in order to grow, and as such, if bushes or trees are found around the HSCW or in the HSCW area, the resulting shade may cause growing difficulties for the macrophytes planted.

MEASURE:

M12 – Visual control of the surface and surrounding area of the HSCW to verify whether there is any growth of trees and/or bushes: Visual control of the surface and surrounding area of the HSCW to verify whether there is any growth of trees and/or bushes.

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC-P5 – Apply recommendations done in problem {P5}

CAUSE:

P7 – Plague of rodents: Rodents may damage vegetation. They may eat seeds, tubers, rhizomes, young shoots and adult plants.

MEASURE:

M15 – Visual control of the HSCW to verify whether there is any evidence of rodents: Visual control of the HSCW to verify the state of the dikes and check that they have not been damaged by rodents. Other signs which show evidence of the presence of these animals are tracks, droppings and holes in the waterproof layer.

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC-P7 – Apply recommendations done in problem {P7}

Table 5.4 (continuation). Technical card of problem {P1} – Abnormal vegetation growth.

CAUSE:

P9 – Water level too high – Formation of surface flow: A water level which is above the tolerance limits of *Phragmites australis* may cause the plant stress, which will negatively affect its growth.

MEASURE:

M5 – Measure the water level: Measure the water level inside the cells using a lysimeter.

M25 – Visual control of the HSCW surface to verify whether there is wastewater flow over the matrix: Visual control of the HSCW surface to verify whether there is wastewater flow over the matrix.

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC-P9 – Apply recommendations done in problem {P9}

CAUSE:

P10 – Water level too low: A water level which is below the tolerance limits of *Phragmites australis* may cause the plant stress, which will negatively affect its growth.

MEASURE:

M5 – Measure the water level: Measure the water level inside the cells using a lysimeter.

ACTION:

AC4 – Other actions to promote the growth of *Phragmites australis*

AC5 – Replanting the plant cover

AC6 – Removing plant debris accumulated in the HSCW area

AC-P10 – Apply recommendations done in problem {P10}

OTHER RECOMMENDATIONS: /

OBSERVATIONS:

- *Occasionally, it is not possible to identify the cause behind the dysfunction. In these situations, once the problem is identified, it is recommended to apply corrective actions without any further control. If no action is recommended, then the WWTP technician can act according to her/his experience.*
- *Actions are described in more detail at the end of the* ***Operating manual****.*

Figure 5.6 shows the EDSS-maintenance interface that provides the guidelines for the problem {P1} – Abnormal vegetation growth, while Figure 5.7 illustrates the corrective action technical card.

EDSS-maintenance is adapted to the characteristics of each facility. Hence, the guidelines recommended in the operating manual vary among different HSCWs. The following paragraphs provide some examples to show the dependency of the operation and maintenance protocols on the wastewater treatment system characteristics, which also justify part of the contents of the operating manual for *Hostalnou de Bianya*.

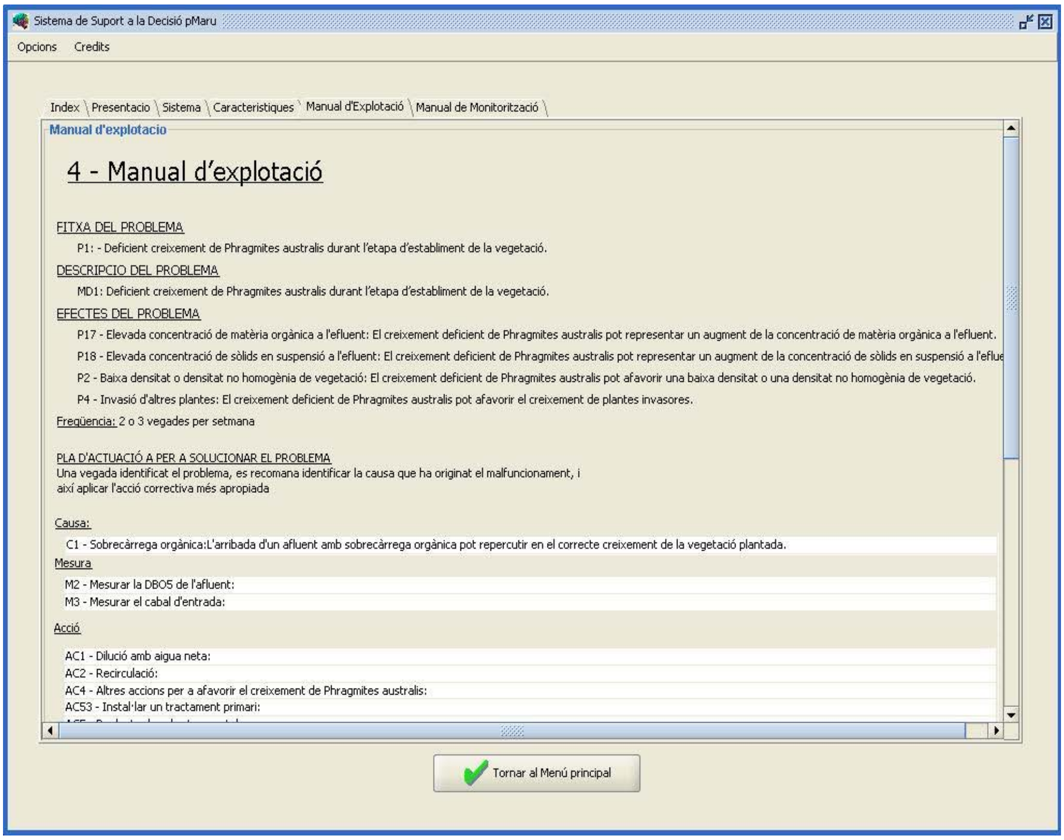

Figure 5.6. EDSS-maintenance interface for the operating manual.
Definition of problem {P1} – Abnormal vegetation growth (in Catalan).

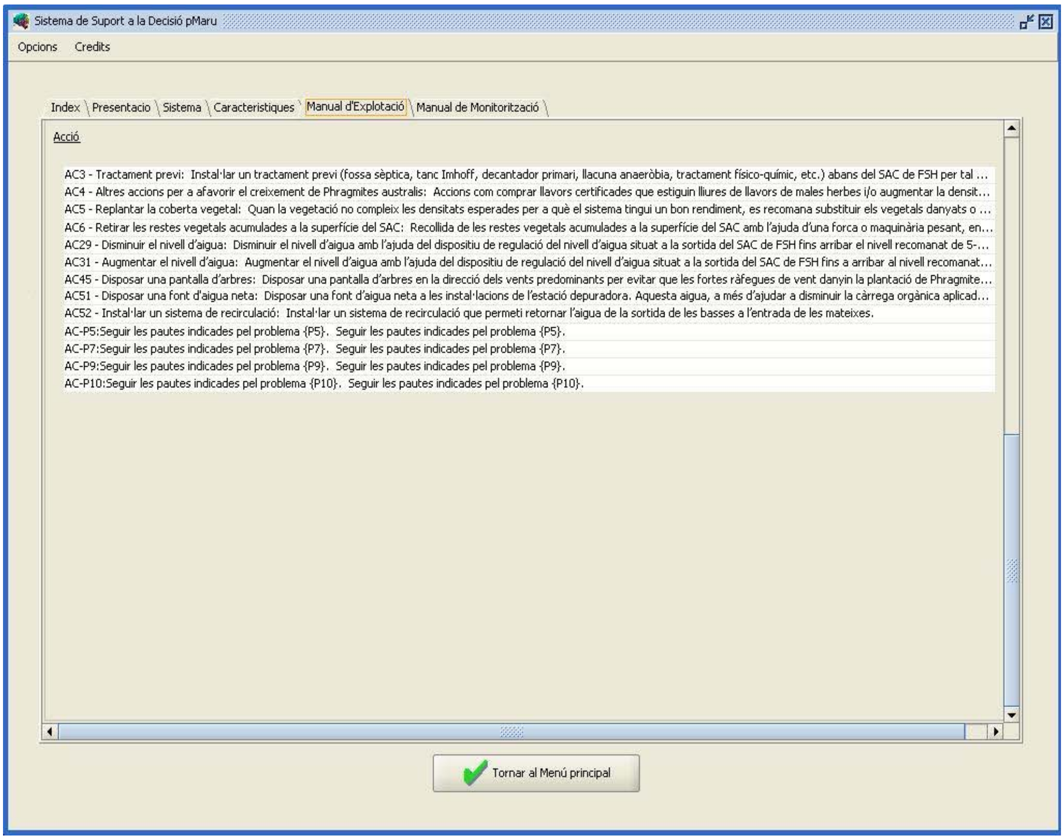

Figure 5.7. EDSS-maintenance interface for the operating manual.
Definition of corrective actions (in Catalan).

The mode definition for a given problem is always the same but the number of modes described in the operating manual varies according to the potential problems identified. For instance, whatever the characteristics of a HSCW are, if the system is less than one year old, problem {P1} – Abnormal vegetation growth will be included in the list of potential failures. As a consequence, mode {MD1} - Poor *Phragmites australis* development during the growth stage will be integrated into the operating manual. Otherwise, i.e. if the HSCW is older than one year, problem {P1} and mode {MD1} will not be described in the operating manual.

Despite some causes of problems being common to all HSCWs, few of them vary among WWTPs. For example, while cause {C5} – Heavy rains can be the origin of problem {P9} – High water level – Water flow over the matrix, in all HSCWs cause {C21} – Inappropriate gravel matrix will only be the starting point of {P8} – Gravel clogging in the HSCWs built with an inappropriate gravel size (Figure 5.8).

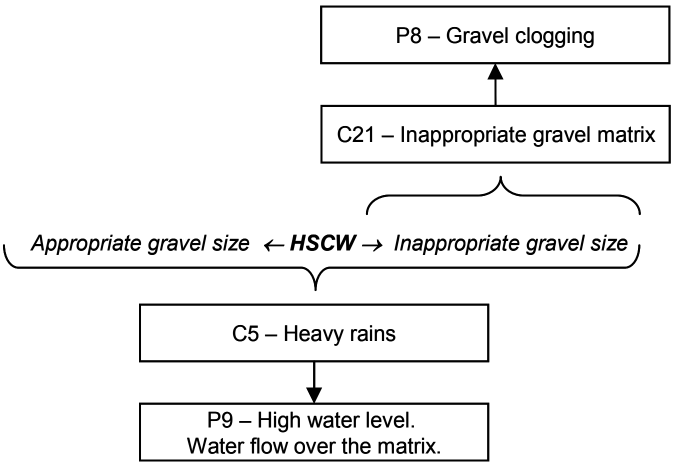

Figure 5.8. Flow diagram with the reasoning path for the identification of causes.

The EDSS-maintenance prototype proposes corrective actions in accordance with (1) the causes that originate the problem, (2) the WWTP configuration and (3) the HSCW design. Figure 5.9 illustrates two examples where the corrective actions differ according to the cause of the problem and the HSCW design. The reasoning process schematized in Figure 5.9.A reflects that if problem {P11} – Unsuitable water distribution is caused by {C27} – Accumulation of suspended solids in the water distribution system (a channel), then EDSS-maintenance will recommend actions {AC3} – Primary treatment and {AC34} – Clean the channel. However, if the origin of {P11} is cause {C28} – Inappropriate design or construction of the channel, the EDSS will propose action {AC35} – Improve the channel. Corrective actions between two wastewater treatment systems can also be different due to two different HSCW designs. As shown in Figure 5.9.B, if problem {P4} – Weed growth appears and the HSCW has a mechanism to modify the water level, then the EDSS-maintenance will recommend action {AC10} – Flood the HSCW. Otherwise, the system will propose action {AC54} – Install a water-level controller.

The intensity of the effects depends on the characteristics of the receiving media: the more sensitive it is, the more intense will be the impact of a problem. Moreover, the kind of effects can vary according to the properties of the spill point. For instance, when problem {P18} – High concentration of suspended solids in the effluent appears and the receiving media is soil, effect {E37} – Clogging of the receiving media can emerge. On the other hand, if the receiving media is a river, then the effect {E36} – Increase in the water turbidity may occur (Figure 5.10).

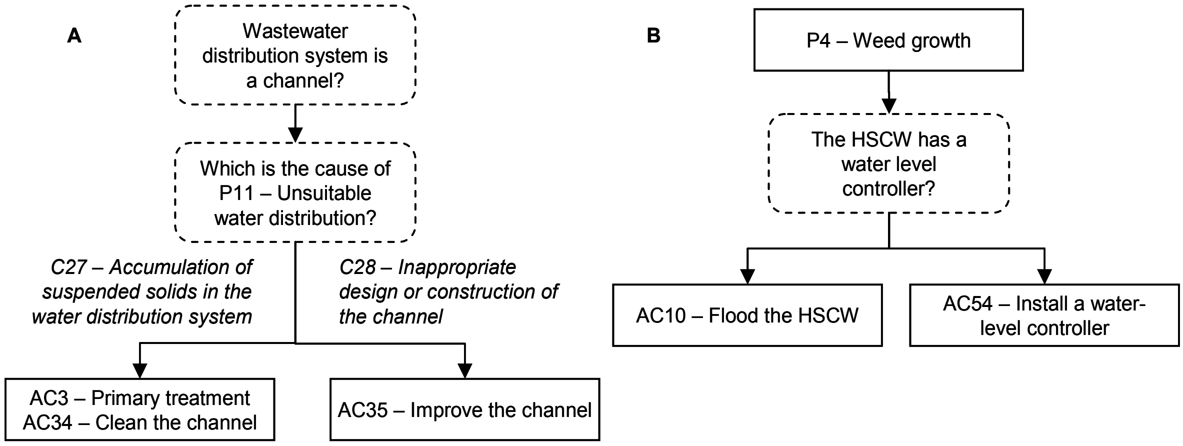

Figure 5.9. Flow diagram with the reasoning path for proposing corrective actions: A) proposed according to the cause behind a problem and, B) proposed according to the HSCW design.

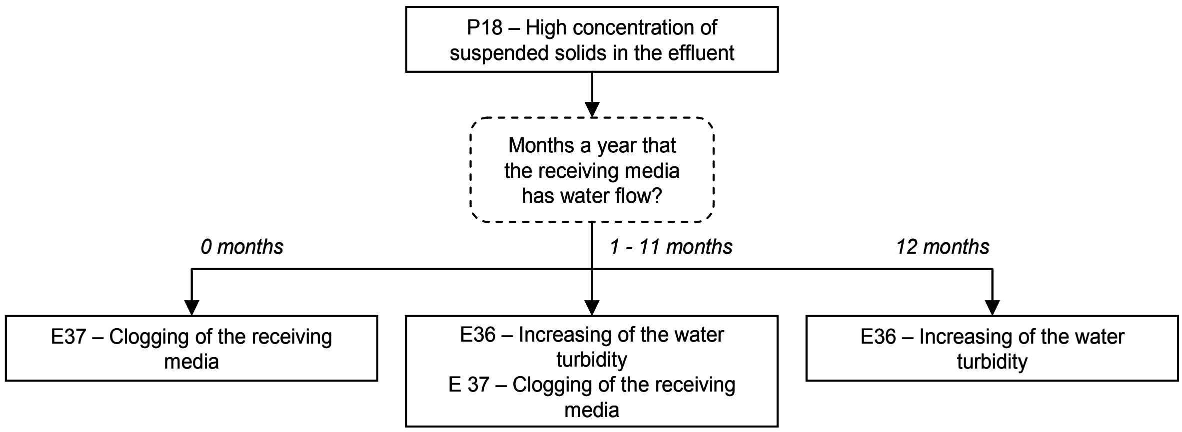

Figure 5.10. Flow diagram with the reasoning path for effects identification.

5.5. Discussion about the EDSS-maintenance prototype

Several studies have been carried out around the world to define the state of the art of constructed wetlands [Boutin *et al.* (1997), Geller (1997), Vandalae *et al.* (2000), Dahab and Surampalli (2001), Vymazal (2002), Griffin (2003), Rousseau *et al.* (2004), Cooper *et al.* (2005), Cooper *et al.* (2006), Puigagut *et al.* (2006), Korkusuz and Diamodopoulos (2006) and Velayos *et al.* (2006)]. From these studies the weak and the strong points of constructed wetlands were identified. A common limitation observed in all constructed wetlands is the lack of know-how about the operation and the maintenance requirements of this technology.

Recently, and in order to confront this lack of technical knowledge, an effort has been made to define guidelines to guarantee, and in some instances to improve, the performance of constructed wetlands. These studies range from (1) the definition of operating and maintenance manuals [EPA (1999), Tousignant *et al.* (1999), Core Group (2000), Kadlec *et al.* (2000) and Korkusuz and Diamodopoulos (2006)], which usually provide general proposals, to (2) recommendations for a particular problem [Blazejewski and Murat-Blazejewska (1997), Mæhlum and Stålnacke (1999), Russell (1999), Higgins and

Mitsch (2001), Thullen *et al.* (2002)], that are commonly particular for a given case study. Despite these studies, no advances have been made in the definition of the most appropriate recommendations according to the characteristics of each constructed wetland.

The knowledge base of the EDSS-maintenance prototype includes information extracted from the literature and interviews with experts on constructed wetlands, but also from the receiving media, the wastewater engineers, etc. All this information was analysed and organized in order to build a reliable knowledge base. This approach led to the inclusion of (1) general information extracted from manuals and (2) particular knowledge extracted from (a) studies done for a particular problem and (b) interviews with experts in different sectors. The objective and systematic merging of both the general and the particular knowledge extracted from different sources allowed the definition of operation and maintenance protocols to be attained according to the characteristics of each HSCW.

Another relevant aspect in the EDSS-maintenance prototype is the consideration of the impact of wastewater treated on the receiving media when defining the monitoring programme and the preventive actions for constructed wetlands. This novel characteristic denotes a step forward towards the integration of all significant management and ecological aspects in the integrated water management paradigm, which has been adopted, at the European level, by the Water Framework Directive [European Community (2000)].

Therefore, the monitoring notebook and operating manual included in the operation and maintenance protocols are defined in a practical manner according to the influent characteristics, receiving media, configuration and design of a given HFCW. As pointed out by Russell (1999), although with reference to mosquito management, operational strategies for pollution control will vary from place to place, from time to time, and from design to design. Since different causes can create the same problem, universal corrective actions usually do not work. On the contrary, HFCW operation and maintenance is best achieved with corrective strategies specific to each problem and cause, and sometimes integrating various complementary actions. It has been shown that proper operation and maintenance, apart from avoiding disturbances, could also lead to higher treatment efficiencies of HFCWs [Vymazal (2002) and Meuleman *et al.* (2003)]. Adapting the measures and their frequencies to each facility also results in financial savings because unnecessary control measures are not carried out. Besides, having access to monitoring programs allows the problems to be detected early while preventive actions preclude severe consequences.

The use of EDSS-maintenance guarantees the systematic and objective management of the information registered by the experts and, consequently, facilitates the sharing and rapid re-use of HSCW technical knowledge and experiences among plant managers, helping to overcome the most common causes of operational problems: lack of know-how, loss of knowledge when operators or engineers move on, and lack of required time for knowledge management in the day-to-day operation (i.e. integrating a large amount of data in different formats, reasoning about them and making decisions on the process operation requires time and skilled plant managers).

Because of these positive aspects of the EDSS-maintenance prototype, it is expected that the application of these protocols in real HSCWs will represent a better acceptance of this technology:

a. Administrations because HSCWs will allow the satisfactory treatment of wastewater coming from small communities, with low investment and operating costs.

b. Wastewater technicians because these guidelines will make the day-to-day operation of the WWTPs based on the HSCW technology easier.

c. Ecologists because the correct performance of these facilities will contribute to the maintenance or improvement of the quality of the receiving media, using a technology which is characterized to provide a wildlife habitat for many wetland organisms and to fit harmoniously into the landscape.

d. Inhabitants of the community because of the improvement in the quality of the receiving media with a WWTP which enhance the aesthetic of the space and, what is more, without nuisances such as noise, mosquitoes and bad smells.

6. Conclusions

6. Conclusions

In 2003 the Catalan Water Agency set up the development of an EDSS to support the definition of operation and maintenance protocols for WWTPs involved in wastewater collection and treatment programme (EDSS-maintenance). This thesis has been developed within this project framework and aims to build a prototype of EDSS-maintenance to define operation and maintenance protocols for HSCW technology.

The most relevant conclusions arising from the research work involved in the development of the EDSS-maintenance prototype are listed below. With respect to state of the art of the HSCWs we conclude that:

- HSCW is an appropriate technology to treat wastewater from small communities because it can provide high treatment efficiency with low energy consumption and low investment costs. In addition, compared to high-loaded systems, they are easier to operate and more efficient to maintain because they have few mechanisms, on-line controllers, sensors, etc. and operation and maintenance activities are focused on maintaining the water level, guaranteeing water distribution, avoiding matrix clogging, assuring plant health, etc.

- Despite being appropriate and sustainable for wastewater treatment for small communities, HSCW operation and maintenance are crucial to guaranteeing their performance. The notion that natural systems are able to manage themselves is false: deficient supervision is the most common cause of disturbances in HSCWs. Another cause of operational problems is the lack of know-how in terms of: (1) the physical, chemical and biological processes occurring in a HSCW and (2) the tasks needed to carry out these processes. Both operational problems (deficient supervision and lack of technical knowledge) have been detected in the Catalan HSCWs.

- In the literature we have found some operation and maintenance manuals, but all of them provide general recommendations which do not usually work because the operation and maintenance requirements vary among HSCWs according to (1) the characteristics of the community, (2) the configuration and design of the WWTP and (3) the characteristics of the receiving media. Moreover, some in-depth studies of certain problems have been published in journals and reports, but this information is specific to a given case study and since the operation and maintenance requirements vary among HSCWs, sometimes, it is not possible to apply the recommendations arrived at these case studies to another WWTP. Hence, a way to support the performance of HSCW (avoid the inappropriate supervision and the lack of know-how) is to combine both kinds of experiences and define management protocols with operation and maintenance proposals suitable for the characteristics of each facility.

- Nowadays (October 2006) there are 13 HSCWs operating in Catalonia but an increase up to 400 facilities is expected. Hence, although at present the necessity of operation and maintenance protocols adapted to the characteristics of each facility can be easily confronted, the objective and systematic definition of operation and maintenance protocols will become essential when the new HSCWs are constructed.

The conclusions of the development of the EDSS-maintenance prototype are:

- The EDSS-maintenance prototype was developed using the five-step methodology proposed by Poch *et al.* (2004). Despite that all the five steps were completed during the construction of this support tool several modifications were introduced in order to adapt the methodology to our environmental problem.

- The first adaptation of the methodology proposed in Poch *et al.* (2004) consisted of categorization to analyse the data and knowledge acquired in the second step (4.2. Data collection and knowledge acquisition).
  - In order to identify and characterise the HSCW problems, a literature review was carried out. This information was updated with the information extracted from the interviews of the technicians of the 13 Catalan HSCWs.
  - The information extracted from the literature and the questionnaires was based on the experience of HSCW experts, hence it was objective and sometimes not validated by the rest of the HSCW researchers, and that is why:
    - Some contradictions in terms of how to prevent a problem, how to apply a corrective action, the frequencies of the controls, etc. have been found among HSCW experts.
    - Certain difficulties were observed when identifying and defining the problems: What is a problem? What is a cause? etc.
  - To confront these inconsistencies, the information acquired from these sources (literature and questionnaire) was analysed using categorization. This analysis allowed:
    - Each problem to be identified and characterized.
    - The relationships among problems to be identified and characterized.
  - From the analysis of the information acquired, it was possible to identify 18 problems: 6 related to the vegetation, 5 concerning the hydraulic retention time, 3 about the HSCW structures, 2 related to the quality of the effluent and finally one regarding the production of bad smells and another one about the presence of rodents. Every problematic situation has been characterized in terms of modes (18), effects (31), causes (49), measures (38) and actions (69).

- The evaluation process of an EDSS is still an open problem and no clear strategies have been established to confront the more critical phases of the development of an EDSS. Hence, the second modification was focused on the improvement of the evaluation process (4.5. Evaluation process).
  - To evaluate EDSS-maintenance we proposed a methodology based on four steps: (1) verification, (2) laboratory validation with historical data, (3) laboratory validation with experts and (4) field validation. This evaluation process has a certain associated complexity because of the impossibility of checking all the scenarios, the scarce and poor quality of the historical data and the subjectivity attributed to the experts in the evaluation of these protocols.
  - To quantify how *good* the EDSS-maintenance prototype is, we have proposed a mathematical function (Equation-1, 4.5.2. Laboratory validation) which compares the results provided by EDSS-maintenance with the "reality" (historical data and experts). Despite the historical data being

unsuitable and the expert validations being subjective, this mathematical function allowed an initial approach to the quantification of the efficiency of the EDSS-maintenance prototype.

  - To assess whether the EDSS-maintenance prototype knowledge base has to be modified or not we developed another mathematical function (Equation-2, 4.5.2. Laboratory validation). This function considers the probability that an item codified in the knowledge base can be found in (1) historical cases, (2) expert experiences and (3) the EDSS proposals. This equation applies homogeneous criteria to evaluate every potential change in the knowledge base.

- Although the EDSS-maintenance prototype has been built using RBS the knowledge representations made in the knowledge implementation and the organization of rules in groups (a group of rules for each problem) (4.4. Model implementation and integration) facilitate the revision, upgrading and enlargement of the knowledge base.

- The combination of Java and Drools software tools allowed a much very easy codification of the HSCW information as well as the representation of the processed information by means of user-friendly interfaces.

- To obtain the operation and maintenance protocol for a given HSCW the user must introduce 48 parameters through 4 different user-interfaces (community characteristics, WWTP characteristics, HSCW design and receiving media properties). Only 26 of these parameters are essential to define the monitoring notebook and the operating manual.

  Once the essential parameters are introduced, the reasoning process starts and the rules are fired until the complete definition of the operation and the maintenance protocols have been made. There are 6 output data interfaces: (1) index of the operation and maintenance protocol, (2) preface of the operation and maintenance protocol, (3) description of the HSCW technology, (4) parameters used in the definition of the operation and maintenance protocols, (5) operating manual and (6) monitoring notebook.

- Along with the development of the EDSS-maintenance prototype, several recommendations to build full EDSS-maintenance have been proposed. These suggestions are based on the modifications of the five-step methodology and the experience gained during the development of the EDSS-maintenance prototype. The first objective of these recommendations is to improve data and knowledge acquisition (quantity and quality). Afterwards they are focused on the analysis and representation phase of this knowledge, and finally they conclude with some advice for EDSS-maintenance evaluation.

About the operation and maintenance protocols provided by the EDSS-maintenance prototype we can conclude that:

- The operation and maintenance protocols proposed by the EDSS-maintenance prototype provide recommendations on how to prevent, detect and solve problematic situations. All these advice are made according to the characteristics of each HSCW facility.

- It is expected that applying the operation and maintenance protocols will support the functioning of HSCWs because:
  - The preventive actions will avoid the appearance of known problems.

  - ▫ The definition of the measures and their frequencies will detect the problems as soon as they appear without the need to perform extra-controls.
  - ▫ The corrective actions will allow a problem solution through the application of the most appropriate action.

  Moreover, the application of the operation and maintenance protocols will contribute to the maintenance or improvement of the receiving media quality.

- Since the operation and maintenance protocols recommend the type and frequency of the required measures and actions, the application of these protocols will:
  - ▫ Make the day-to-day tasks of the HSCW technicians easier.
  - ▫ Facilitate administrative control by the Catalan Water Agency.
  - ▫ Represent a financial savings because no-extra measures and/or actions will be taken.

Therefore, we can conclude that the objectives fixed at the beginning of this thesis have been fulfilled:

√ We have developed a prototype of the EDSS-maintenance which allows solving the environmental problem of guaranteeing the performance of HSCWs through the definition of operation and maintenance protocols according to the characteristics of each facility.

√ Moreover, the development of this prototype has permitted us to establish the guidelines to develop the full EDSS-maintenance.

Although we have fulfilled the objectives of the thesis and we have provided a solution to the environmental problem detected by the Catalan Water Agency, new challenges can be confronted in respect to (1) the HSCW technology and (2) the development of the full EDSS-maintenance. Future work for the HSCW management can be focused on the following aspects:

– An HSCW can treat *raw* wastewater or wastewater pre-treated in another treatment unit: primary treatment (e.g. septic tank or Imhoff tank) or secondary treatment (e.g. activated sludge or waste stabilization pond). The characteristics of the wastewater will be different in each situation and the performance of the HSCW will vary according to them, but how these combinations can affect the management requirements?

– Low-loaded technologies, such as HSCWs, can be distinguished from high-loaded techniques by the fact that this type of facility can operate without electricity because they do not require online controllers, sensors, etc. But could these elements (e.g. an online flow-rate or an online water level controller) make the management of HSCW easier?

– Wastewater technicians have labelled HSCWs as an *unbending* wastewater treatment technology because there are not usually equipped with elements which allow confronting hydraulic overloads, organic overloads, unsuitable weather conditions, etc. Along the thesis some actions have been proposed to confer to the HSCW the capacity to adapt to such variations (e.g. install a recirculation system or install a mechanism to dosify wastewater), however could we find other elements to provide more operational flexibility to an HSCW?

- The knowledge about small WWTP management is scarce and inconsistent. Hence a major effort must be made to acquire more knowledge from HSCW that are nowadays operating in Catalonia or in surrounding regions. This knowledge acquisition can be performed by means of questionnaires or onsite studies, but whatever the procedure selected the contribution of WWTP operators is crucial.

In Chapter 4 several recommendations have been posed to develop the full EDSS-maintenance. These proposals are linked to data and knowledge that will be acquired for the other technologies involved in the EDSS-maintenance. Hence, we propose to focus the future work for the EDSS-maintenance development in the evaluation process, (i) the only proposal which not depends on the information that will be acquired and, moreover, (ii) that it is an important issue to solve in the development of EDSSs. The matters that we propose to study are:

- How to verify and validate the full knowledge base?

  The complexity of environmental problems hinders the identification of a reduced set of scenarios to be used for evaluation that really guarantees a good representation of the whole system behaviour. One way to solve this issue is to define and test the scenarios that cover the normal situations as well as some extreme or abnormal situations detected or foreseen, but:

  1) What is a normal situation?
  2) What is an extreme or abnormal situation?
  3) How many situations must be tested to affirm that the knowledge base is reliable?

- How to quantify the goodness of the EDSS?

  The Equation-1 (4.5.2. Laboratory validation) allows estimating the goodness of the EDSS-maintenance prototype defining operation and maintenance protocols. However this application has to be considered a simple approach at the EDSS evaluation because several challenges must be confronted:

  1) Could be possible to tackle the compensation phenomena in the Equation-1?
  2) How to confront the possible poor quality of the comparison references?
  3) How many situations must be tested to affirm that the EDSS is reliable?

- How to decide whether the EDSS knowledge base must be modified?

  The Equation-2 (4.5.2. Laboratory validation) evaluates the probability in which a specific result can be found in historical cases, expert experiences and EDSS proposals. From this value can be taken the decision of removing or including a certain item in the EDSS knowledge base, but:

  1) The three comparison references (historical cases, expert experiences and EDSS proposals) must be pondered?
  2) How to fix the value from which an item has to be removed or included in the knowledge base?
  3) How many situations must be tested to decide whether an item has to be removed on included in the knowledge base?

7. References

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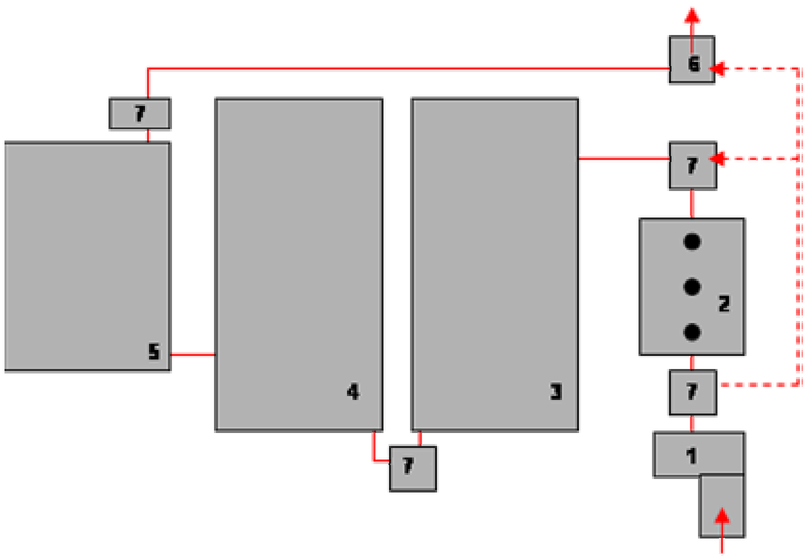
Annex I – Questionnaire

Annex I – Questionnaire

This annex presents the results of the questionnaires given to HSCW users in Catalonia. For each of the 13 constructed wetlands subject to interview procedure there are a total of 4 tables: Inventory, WWTP configuration, the design of the HSCW and management.

Table A1.1. Inventory for the HSCW of *Alfés*.

Community		
Town	*Alfés*	
Region	*Segrià*	
Year of construction /start of operation	2002	
WWTP configuration		
Pre-treatment	Thick screen	
Primary	Septic tank	
Secondary	HSCW	
Tertiary	Waste stabilization pond	
Diagram		



1. Inlet and pre-treatment; **2.** Septic tank; **3** and **4.** HSCW;
5. Waste stabilization pond; **6.** Outlet; **7.** Wastewater distributor
Water conductsand *By pass*

Parcel		
Distance to community	500 m	
Distance to receiving media	2 m	
Parcel area	12,000 m^2	
Distance to trees and/or bushes	There are no trees or bushes	
Altitude above sea level	236 m	
Electricity	No	
Perimeter fence	Yes, wire, 2 m high with an access gate (2 x 4 m) 3 m from the cells	
Wastewater details		
Population	352 inhabitants	
Seasonal population	No	
Industrial activity	No	
Treated wastewater		
	Performances	***Outlet***
SS	85.87%	42 mg/l
BOD_5	94.49%	22 mg/l
COD	85.56%	98 mg/l

Table A1.2. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *Alfés*.

Pre-treatment

Description

Thick screen: Metallic grid, manually cleaned, with 3-4cm mesh opening.

Diagram or photograph

Primary treatment

Description

Septic tank with 3 units and a capacity of 40,000 l.

Diagram or photograph

Tertiary treatment

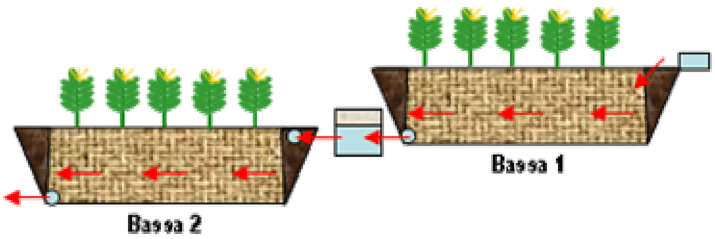
Description

Waste stabilization pond: 1.6 m deep with a surface area of 35 x 35 m.

Diagram or photograph

Table A1.3. Design of the HSCW of *Alfés*.

Diagram of the HSCW



Characteristics of the cells						
Cell number		**1**	**2**	**3**	**4**	**5**
Length		32.5 m	32.5 m			
Width		38 m	36.5 m			
Depth *		0.54 m	0.7 m			
Base inclination *		0.36%	0.5%			
Interior dike inclination *		45%	45%			
Exterior dike inclination *		Land-based cells	Land-based cells			
Safety margin *		20 cm	20 cm			
Covering*		/	/			
Waterproofing		Membrane	Membrane			
Matrix *						
diameter	**A**	20-40 mm	20-40 mm			
	B	8-12 mm	8-12 mm			
	C	20-40 mm	20-40 mm			
thickness	**A**	1 m	1 m			
	B	The remainder	The remainder			
	C	1 m	1 m			
Vegetation						
Cell number		**1**	**2**	**3**	**4**	**5**
Species		*Phragmites, Thypa, Scirpus and Iliris*	*Phragmites, Thypa, Scirpus and Iliris*			
Plantation density		4 plants/m^2	4 plants/m^2			
Plantation system		Plants	Plants			
Distribution systems and wastewater collection						
Cell number		**1**	**2**	**3**	**4**	**5**
Inlet *		Constructed channel	Corrugated tube			
Outlet *		Corrugated tube	Corrugated tube			
Between cells		Gravity	Gravity			
By pass		Yes, after pre-treatment to Pool 1 and/or to the receiving media.				

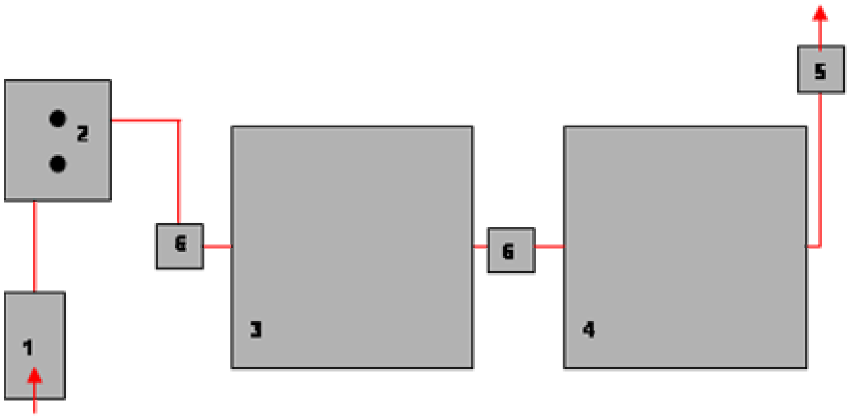
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.4. Summary file of maintenance carried out in the HSCW of *Alfés*.

Visits to the WWTP
Frequency: 2-3 visits per week **Description:** The pre-treatment system (grid) is cleaned, the water distribution system is checked to ensure that it functions correctly, and the state of the cell is checked. Herbicide is applied to the plants which grow on the paths.
Vegetation control
Cutting frequency (season): Twice a year (spring – winter) **What happens to the debris?** It is transported to the tip **Weed removal:** Weeds are pulled up manually after cutting has been carried out. Those that grow on the edges are pulled up as soon as they are detected. **Treatment of diseases/fungal infections/others:** /
Insects
When were they detected? / **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: The cells have surface flux at the inlet zone. This results in the formation of patches without vegetation. **Actions carried out:** The plant has lysimeters in order to observe the water level in each cell. **Why and when the water level varies:** The water level is reduced to minimum levels before the cutting period in order to ensure that the cutting machinery does not damage the cells. **Degree of variation:** Minimum level.
Bad smells
No significant occurrence of bad smells has been detected
Distribution systems
What problems occur? The distribution system is channel-type and does not cause problems **How are the problems solved?** /
Waterproofing
No imperfections of any type were found.

Table A1.5. Inventory for the HSCW of *Almatret Nord*.

Community	
Community	*Almatret Nord*
Region	*Segrià*
Year of construction/Initial operations	2001 – 2002
WWTP configuration	
Pre-treatment	Thick and fine screen
Primary	Septic tank
Secondary	HSCW
Tertiary	Waste stabilization pond
Diagram	



1. Inlet and pre-treatment; **2.** Septic tank; **3.** HSCW; **4.** Waste stabilization pond; **5.** Outlet; **6.** Wastewater distributor

Parcel	
Distance to community	2,000 m
Distance to receiving media	2 m
Parcel area	2,200 m^2
Distance to trees and/or bushes	There are no trees
Altitude above sea level	462 m
Electricity	No
Perimeter fence	Yes, wire, 1.6 m high with an access gate (2 x 4 m), 3 m from the cells
Wastewater details	
Population	516 inhabitants
Seasonal population	No
Industrial activity	No

Treated wastewater		
	Performances	***Outlet***
SS	72.79%	39 mg/l
BOD_5	96.48%	10 mg/l
COD	84.30%	91 mg/l

Table A1.6. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *Almatret Nord*.

Pre-treatment

Description

Thick screen: Metallic grid, manually cleaned, with 4 cm mesh opening.
Fine screen: Metallic grid, manually cleaned, with 1cm mesh opening.

Diagram or photograph

Thick screen

Fine screen

Primary treatment

Description

Septic tank with a capacity of 30,000 l.

Diagram or photograph

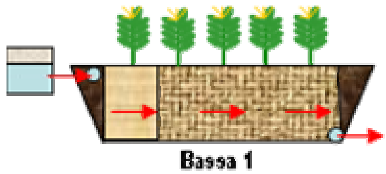
Tertiary treatment

Description

Waste stabilization pond: 0.5 m deep with a surface area of 500 m^2.

Diagram or photograph

Table A1.7. Design of the HSCW of *Almatret Nord*.

Diagram of the HSCW						
						
Characteristics of the cells						
Cell number		**1**	**2**	**3**	**4**	**5**
Length		21.7 m				
Width		21.5 m				
Depth *		0.6 m				
Base inclination *		1.5%				
Interior dike inclination *		66.6%				
Exterior dike inclination *		Inlet: 0% Sides: 66.6%				
Safety margin *		25-30 cm				
Covering*		Compacted earth				
Waterproofing		Membrane				
Matrix *						
diameter	**A**	40-60 mm				
	B	18-20 mm				
	C	8-12 mm				
	D	40-60 mm				
thickness	**A**	50-75 cm				
	B	100-150 cm				
	C	The remainder				
	D	50-75 cm				
Vegetation						
Cell number		**1**	**2**	**3**	**4**	**5**
Species		*Phragmites*				
Plantation density		4 plants/m^2				
Plantation system		Plants				
Distribution systems and wastewater collection						
Cell number		**1**	**2**	**3**	**4**	**5**
Inlet *		Perforated tube				
Outlet *		Corrugated tube				
Between cells		Gravity				
By pass						

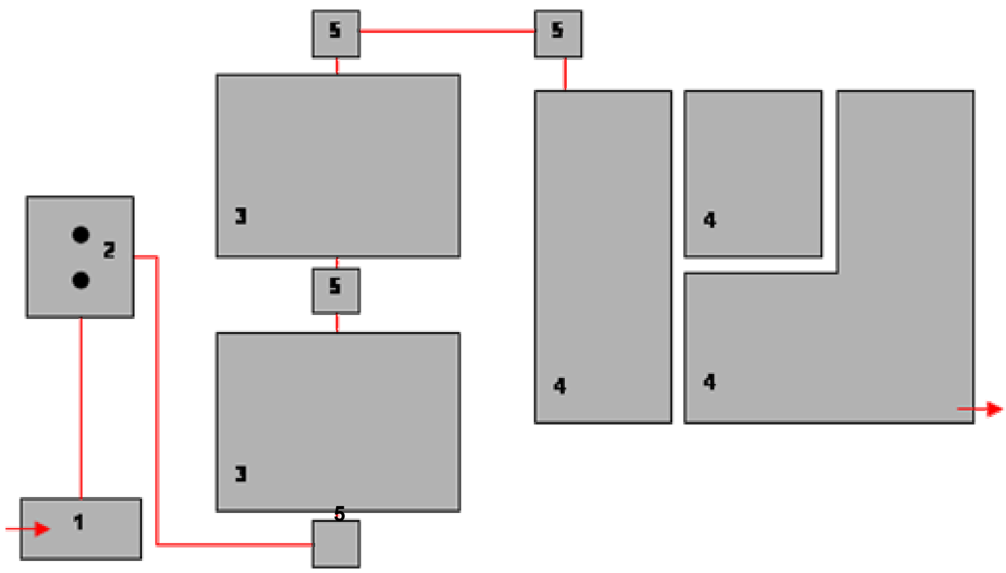
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.8. Summary file of maintenance carried out in the HSCW of *Almatret Nord*.

Visits to the WWTP
Frequency: 2 – 3 visits per week. **Description:** The pre-treatment system (grid) is cleaned, the water distribution system is checked for blockages, and the state of the cells is checked. Herbicide is applied to the plants which grow on the paths.
Vegetation control
Cutting frequency (season): Twice a year (spring-winter) **What happens to the debris?** It is left to dry on nearby land. **Weed removal:** Weeds are pulled up manually after cutting has been carried out. Those that grow on the edges are pulled up as soon as they are detected. **Treatment of diseases/fungal infections/others:** At the end of August a white grub was in *Phragmites australis* and the plant turns yellow. As cutting was soon to be carried out, this procedure was implemented and the plague was eliminated.
Insects
When were they detected? / **Treatment of the problem: /**
Rodents
When were they detected? / **Treatment of the problem: /**
Water level
Surface flux: / **Actions carried out: /** **Why and when the water level varies:** The water level is reduced to minimum levels before the cutting period in order to ensure that the cutting machinery does not damage the cells. **Degree of variation:** Minimum level.
Bad smells
No significant occurrences have been detected.
Distribution systems
What problems occur? The holes in the distribution tubes may get blocked. **How are the problems solved?** The holes are unblocked during routine visits to the plant. In addition, once a month, water is hosed through the tube in order to clean the inner surfaces.
Waterproofing
No imperfections of any type were found.

Table A1.9. Inventory for the HSCW of *Almatret Sud*.

Community	
Community	*Almatret Sud*
Region	*Segrià*
Year of construction/Initial operations	2001-2002
WWTP configuration	
Pre-treatment	Thick and fine screen
Primary	Septic tank
Secondary	HSCW
Tertiary	Waste stabilization pond
Diagram	



1. Inlet and pre-treatment; **2.** Septic tank; **3.** HSCW; **4.** Waste stabilization pond; **5.** Wastewater distributor

Parcel	
Distance to community	2,000 m
Distance to receiving media	2 m
Parcel area	6,560 m^2
Distance to trees and/or bushes	There are no trees
Altitude above sea level	462 m
Electricity	No
Perimeter fence	Yes, wire, 1.6 m high with an access gate (2 x 4 m), 3 m from the cells
Wastewater details	
Population	516 inhabitants
Seasonal population	No
Industrial activity	No

Treated wastewater		
	Performances	***Outlet***
SS	41.44%	103 mg/l
BOD_5	84.76%	47 mg/l
COD	77.08%	130 mg/l

Table A1.10. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *Almatret Sud*.

Pre-treatment

Description

Thick screen: Metal grid, manually cleaned with an opening of 4 cm.
Fine screen: Metal grid, manually cleaned with an opening of 1 cm.

Diagram or photograph

Thick screen

Fine screen

Primary treatment

Description

Septic tank with a capacity of 50,000 l.

Diagram or photograph

Tertiary treatment

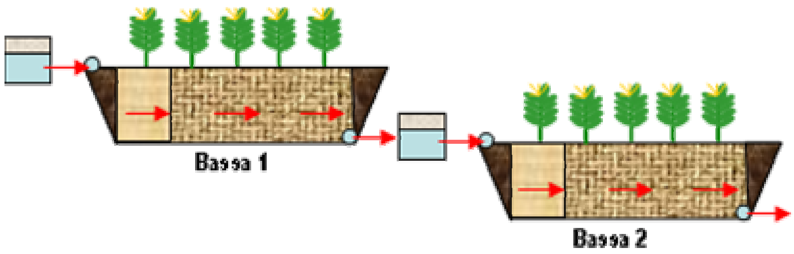
Description

Waste stabilization pond: There are three cells of 821, 524 and 1,407 m^2.

Diagram or photograph

Table A1.11. Design of the HSCW of *Almatret Sud*.

Diagram of the HSCW



Characteristics of the cells						
Cell number		**1**	**2**	**3**	**4**	**5**
Length		21.8 m	25.5 m			
Width		17 m	18 m			
Depth *		0.6 m	0.6 m			
Base inclination *		1.5%	1.50%			
Interior dike inclination *		66.6%	66.6%			
Exterior dike inclination *		Land-based cell	Land-based cell			
Safety margin *		20-25 cm	20-25 cm			
Covering*		Constructed	Constructed			
Waterproofing		Membrane	Membrane			
Matrix *						
diameter	**A**	40-60 mm	40-60 mm			
	B	8-12 mm	8-12 mm			
	C	40-60 mm	40-60 mm			
thickness	**A**	50-75 cm	50-75 cm			
	B	The remainder	The remainder			
	C	50-75 cm	50-75 cm			
Vegetation						
Cell number		**1**	**2**	**3**	**4**	**5**
Species		*Phragmites*	*Phragmites*			
Plantation density		4 plants/m^2	4 plants/m^2			
Plantation system		Plants	Plants			
Distribution systems and wastewater collection						
Cell number		**1**	**2**	**3**	**4**	**5**
Inlet *		Perforated tube	Perforated tube			
Outlet *		Corrugated tube	Corrugated tube			
Between cells		Gravity	Gravity			
By pass		Yes	Yes			

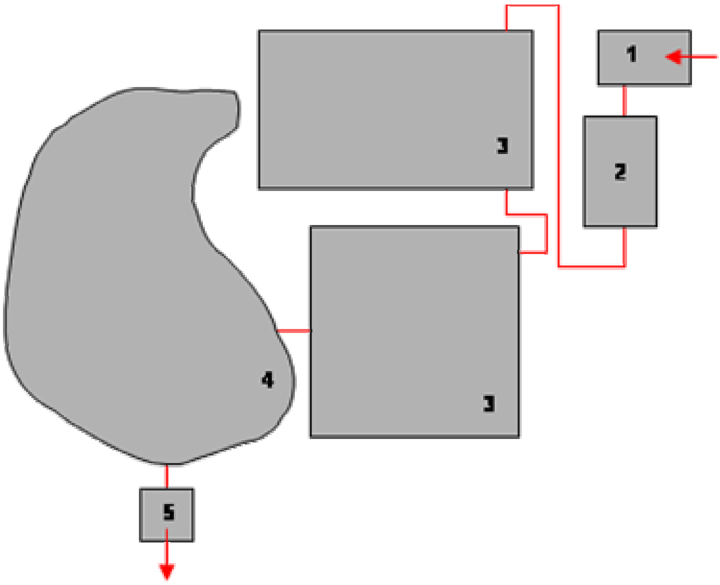
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.12. Summary file of maintenance carried out in the HSCW of *Almatret Sud*.

Visits to the WWTP
Frequency: 2 – 3 visits per year **Description:** The pre-treatment system (grid) is cleaned, the water distribution system is checked to ensure that it functions correctly, and the state of the cells is checked. Herbicide is applied to the plants which grow on the paths.
Vegetation control
Cutting frequency (season): Twice a year (spring-summer) **What happens to the debris?** It is left to dry on nearby land. **Weed removal:** Weeds are pulled up manually after cutting has been carried out. Those that grow on the edges are pulled up as soon as they are detected. **Treatment of diseases/fungal infections/others:** /
Insects
When were they detected? / **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: Several pools of water flow on the first few metres of the cells. **Actions carried out:** The holes are unblocked during routine visits to the plant. In addition, once a month water is hosed through the tube in order to clean the inner surfaces. **Why and when the water level varies:** The water level is reduced to minimum levels before the cutting period in order to ensure that the cutting machinery does not damage the cells. **Degree of variation:** Minimum level.
Bad smells
No significant occurrences have been recorded.
Distribution systems
What problems occur? The holes in the distribution tubes become blocked. **How are the problems solved?** The holes are unblocked during routine visits to the plant. In addition, once a month, water is hosed through the tube in order to clean the inner surfaces.
Waterproofing
No imperfections of any type were found.

Table A1.13. Inventory for the HSCW of *Arnes*.

Community	
Community	*Arnes*
Region	*Terra Alta*
Year of construction/Initial operations	1997-1999
WWTP configuration	
Pre-treatment	Thick and fine screen
Primary	Imhoff tank
Secondary	HSCW and surface flow constructed wetland
Tertiary	/
Diagram	



1. Inlet and pre-treatment; **2.** Imhoff tank; **3.** HSCW;
4. Constructed surface flow wetlands; 5. Wastewater distributor
——— Water conducts and - - - - - - *By pass*

Parcel		
Distance to community	8,000 m	
Distance to receiving media	800 m	
Parcel area	18,951 m^2	
Distance to trees and/or bushes	Trees were planted on the perimeter of the surface flow constructed wetland.	
Altitude above sea level	568 m	
Electricity	No	
Perimeter fence	No	
Wastewater details		
Population	552 inhabitants	
Seasonal population	1,852 inhabitants in summer	
Industrial activity	Oil co-op, mechanic workshop and wine co-op	
Treated wastewater		
	Performances	***Outlet***
SS	71.59%	34 mg/l
BOD_5	90.06%	20 mg/l
COD	83.08%	72 mg/l

Table A1.14. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *Arnes*.

Pre-treatment

Description

Thick screen: Concrete tank 1.5 x 1.5 x 1.5 m^3, with a 400 mm *by pass* inside.
Fine screen: Vertical sieve with 20 mm openings. Located in a brick shed.

Diagram or photograph


Thick screen


Fine screen

Primary treatment

Description

Imhoff tank

Diagram or photograph


Detail of the outlet of the Imhoff tank

Tertiary treatment

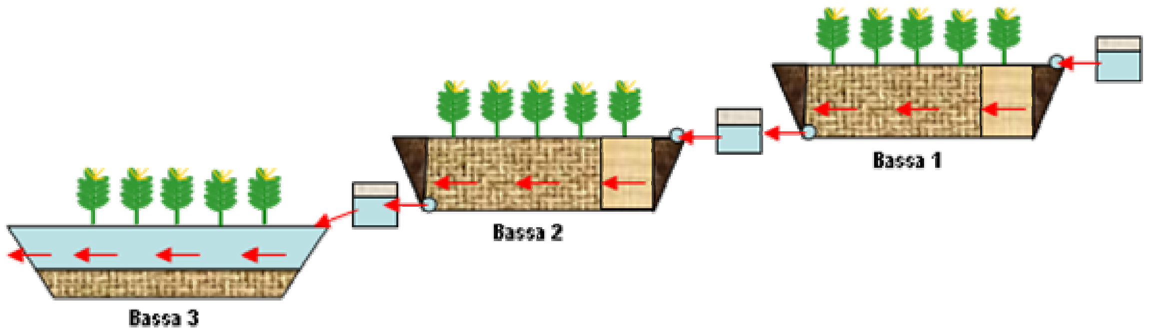
Description

/

Diagram or photograph

Table A1.15. Design of the HSCW of *Arnes*.

Diagram of the HSCW



Characteristics of the cells						
Cell number		**1**	**2**	**3**	**4**	**5**
Length		75 m	75 m	5,900 m^2		
Width		25 m	25 m			
Depth *		0.5 m	0.5 m	0.5-1 m		
Base inclination *		1%	1%	0%		
Interior dike inclination *		/	/	/		
Exterior dike inclination *		Land-based cell	Land-based cell	Land-based cell		
Safety margin *		30-35 cm	30-35 cm	10 cm		
Covering*		/	/	/		
Waterproofing		Compacted earth	Compacted earth	Compacted earth		
Matrix *						
diameter	**A**	20-100 mm	20-100 mm	Original soil, compacted and tilled		
	B	2-10 mm	2-10 mm			
	C	20-100 mm	20-100 mm			
thickness	**A**	1 m	1 m			
	B	The remainder	The remainder			
	C	1 m	1 m			
Vegetation						
Cell number		**1**	**2**	**3**	**4**	**5**
Species		*Phragmites*	*Phragmites*	*Phragmites* and *Scirpus*		
Plantation density		Carpet areas of 25 cm x 75 m		4 plants/m^2		
Plantation system		Rhizomes	Rhizomes	Plants		
Distribution systems and wastewater collection						
Cell number		**1**	**2**	**3**	**4**	**5**
Inlet *		Perforated tube	Perforated tube			
Outlet *		Corrugated tube	Corrugated tube			
Between cells		Gravity	Gravity			
By pass		Yes, in the inlet (thickness well zone) there is a *by pass* to the receiving media				

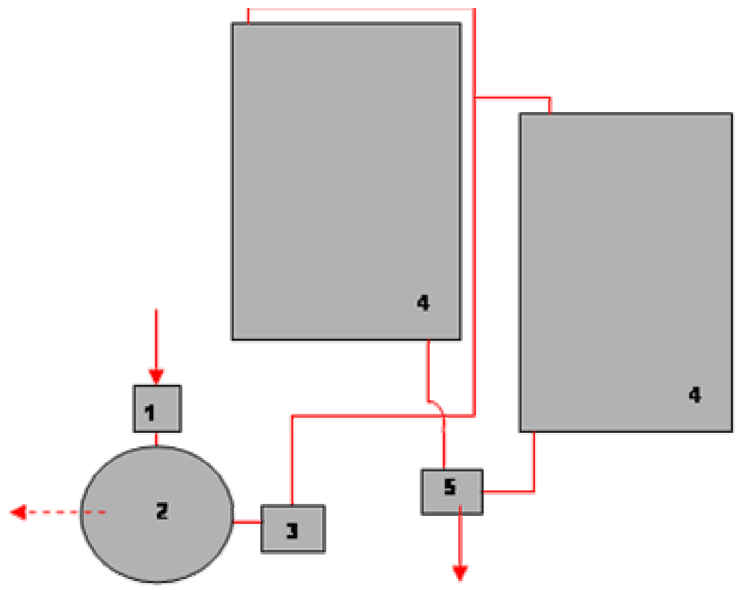
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.16. Summary file of maintenance carried out in the HSCW of *Arnes*.

Visits to the WWTP
Frequency: 1 visit per day **Description:** The pre-treatment system is cleaned and the cells are checked to ensure that they are in an adequate condition. The weeds which grow on the paths are also removed.
Vegetation control
Cutting frequency (season): Once a year (winter) **What happens to the debris?** It is burned outside the plant area. **Weed removal:** The weeds which grow inside the cells are not removed. Those which grow on the paths are cut or pulled up. **Treatment of diseases/fungal infections/others:** /
Insects
When were they detected? Beehives have been detected in the area outside the plant in summer, and may cause problems to the plant operators. **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: There is surface flux on 25% of the surface area of the first cell. **Actions carried out:** When this phenomenon is observed, the operator closes the inlet valve temporarily so that more water enters the cell which is operating in parallel until the water reaches an adequate level. **Why and when the water level varies:** The water level is reduced when cutting takes place and personnel have to enter the cells. **Degree of variation:** Minimum level.
Bad smells
Important occurrences have not been detected.
Distribution systems
What problems occur? The distribution tubes become blocked. **How are the problems solved?** The outlets are checked for blockages once a week.
Waterproofing
No problems to the waterproofing layer have been observed.

Table A1.17. Inventory for the HSCW of *Cervià de Ter*.

Community	
Community	*Cervià de Ter*
Region	*Gironès*
Year of construction/Initial operations	2002
WWTP configuration	
Pre-treatment	Thick screen
Primary	Imhoff Tank
Secondary	HSCW
Tertiary	/
Diagram	



1. Inlet and pre-treatment; **2.** Imhoff tank; **3.** Pumping; **4.** HSCW; **5.** Wastewater distribution
Water conducts and *By pass*

Parcel		
Distance to community	800 m	
Distance to receiving media	30 m	
Parcel area		
Distance to trees and/or bushes	10 m	
Altitude above sea level		
Electricity	Yes	
Perimeter fence	Yes, wire, 2 m high with an access gate (2 x 4 m) 2 m from the cells	
Wastewater details		
Population	1,300 inhabitants	
Seasonal population	No	
Industrial activity	Farms	
Treated wastewater		
	Performances	***Outlet***
SS	91.14%	17 mg/l
BOD_5	93.44%	18 mg/l
COD	85.30%	94 mg/l

Table A1.18. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *Cervià de Ter*.

Pre-treatment

Description

Thick screen: Metal grid, manually cleaned with an opening of 3 – 4 cm.

Diagram or photograph

Primary treatment

Description

Imhoff tank: Circular tank, 4 m in diameter and 6-7 m deep.

Diagram or photograph

Tertiary treatment

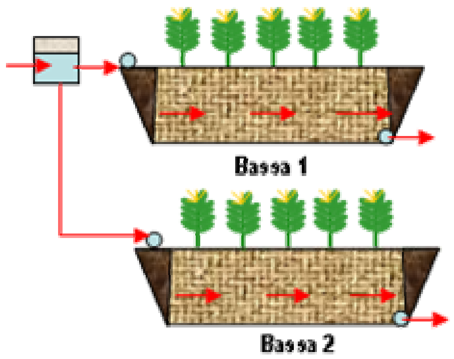
Description

/

Diagram or photograph

Table A1.19. Design of the HSCW of*Cervià de Ter*.

Diagram of the HSCW



Characteristics of the cells						
Cell number		**1**	**2**	**3**	**4**	**5**
Length		65 m	65 m			
Width		25 m	25 m			
Depth *						
Base inclination *						
Interior dike inclination *						
Exterior dike inclination *		Land-based cell	Land-based cell			
Safety margin *		50 cm	50 cm			
Covering*		/	/			
Waterproofing		Membrane	Membrane			
Matrix *						
Diameter	**A**	40-60 mm	40-60 mm			
	B	8-12 mm	8-12 mm			
	C	40-60 mm	40-60 mm			
thickness	**A**	1 m	1 m			
	B	The remainder	The remainder			
	C	1 m	1 m			
Vegetation						
Cell number		**1**	**2**	**3**	**4**	**5**
Species		*Phragmites*	*Phragmites*			
Plantation density						
Plantation system						
Distribution systems and wastewater collection						
Cell number		**1**	**2**	**3**	**4**	**5**
Inlet *		Perforated tube	Perforated tube			
Outlet *		Corrugated tube	Corrugated tube			
Between cells		Gravity	Gravity			
By pass		Yes, from the Imhoff tank to the receiving media.				

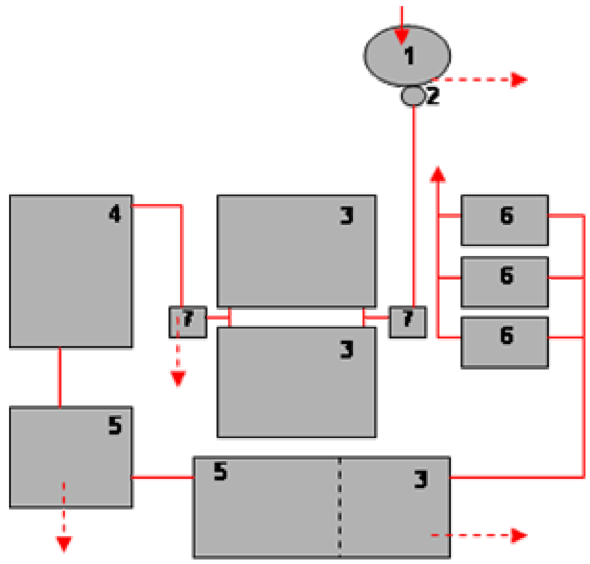
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.20. Summary file of maintenance carried out in the HSCW of *Cervià de Ter*.

Visits to the WWTP
Frequency: 3-4 visits per week **Description:** The large-size material grid is cleaned, and the general condition of the plant is checked. If the holes in the distribution tubes are blocked they are unblocked.
Vegetation control
Cutting frequency (season): Cutting is not carried out. **What happens to the debris?** / **Weed removal:** Those weeds growing on the cells are not removed. The bushes which grow on the edges of the cells, and which may damage the waterproof layer are removed. The weeds which grow on the paths are removed every week. **Treatment of diseases/fungal infections/others:** /
Insects
When were they detected? / **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: The two cells have a free surface flux on 20% of their surface which is caused by the poor functioning of the water distribution tubes (blocked holes). **Actions carried out:** Several holes are to be unblocked so that the distribution of the flow is more constant. **Why and when the water level varies:** Although a tube with an elbow-joint is available, which allows the variation of the water level to the cells, this action is not currently carried out, as the tube and the protection tube are covered by a layer of sulphur which impedes this operation. **Degree of variation:** /
Bad smells
The only times when bad smells have been detected have been due to the accumulation of debris in the council containers which are located on the site.
Distribution systems
What problems occur? The holes in the distribution tubes become blocked. **How are the problems solved?** The holes are unblocked manually.
Waterproofing
The Geotextile is damaged and reeds are growing between the synthetic membrane and the Geotextile.

Table A1.21. Inventory for the HSCW of *Corbins*.

Community	
Community	*Corbins*
Region	*Segrià*
Year of construction/Initial operations	2001
WWTP configuration	
Pre-treatment	Fine screen (located at the outlet of the Imhoff tank)
Primary	Imhoff tank
Secondary	HSCW
Tertiary	Waste stabilization pond + HSCW + Soil filters with macrophytes
Diagram	



1. Inlet and Imhoff tank; **2.** Fine screen; **3.** HSCW;
4. Optional waste stabilization pond; **5.** Aerobic pond; **6.** Soil filters with macrophytes
______ Water conducts and \- \- \- \- \- \- *By pass*

Parcel	
Distance to community	500 m
Distance to receiving media	100 m
Parcel area	28,182 m^2
Distance to trees and/or bushes	2 m
Altitude above sea level	211 m
Electricity	No
Perimeter fence	Yes, wire, 2 m high with an access gate (2 x 4 m) 2 m from the cells.
Wastewater details	
Population	1,500 inhabitants
Seasonal population	2,000 inhabitants in summer
Industrial activity	Butchers and a slaughterhouse

	Treated wastewater	
	Performances	***Outlet***
SS	83.15%	38 mg/l
BOD_5	93.79%	17 mg/l
COD	85.99%	83 mg/l

Table A1.22. Design of pre-treatment, primary treatment and tertiary treatment of the HSCWS of *Corbins*.

Pre-treatment

Description

Fine screen: Basket-shaped metal grid with 1cm opening. Located on the outlet of the Imhoff tank as there is insufficient space on the inlet.

Diagram or photograph

Primary treatment

Description

Imhoff tank: Circular, 7 m high and 10 m in diameter. Fitted with a tap on the lower part in order to facilitate the extraction of assimilated mud.

Diagram or photograph

Tertiary treatment

Description

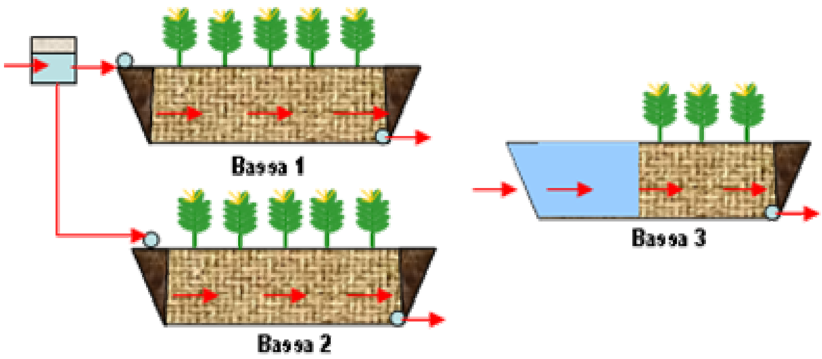
Optional waste stabilization pond 2 m deep, aerobic waste stabilization pond 1.5 m deep, aerobic waste stabilization pond 1 m deep and combined with a HSCW and 3 soil filters with macrophytes.

Diagram or photograph



Table A1.23. Design of the HSCWS of *Corbins*.

Diagram of the HSCW



Characteristics of the cells						
Cell number		**1**	**2**	**3**	**4**	**5**
Length		35 m	35 m	27 m		
Width		36 m	36 m	27 m		
Depth *		0.6-0.8 m	0.6-0.8 m	0.6 m		
Base inclination *		2%	2%	1.5%		
Interior dike inclination *		1.5%	1.5%	1.5%		
Exterior dike inclination *		1.5%	1.5%	Land-based cells		
Safety margin *		20-25 cm	20-25 cm	20-25 cm		
Covering*		Fine gravel	Fine gravel	/		
Waterproofing		Membrane	Membrane	Membrane		
Matrix *						
diameter	**A**	40-60 mm	40-60 mm	80-100 mm		
	B	18-20 mm	18-20 mm	10-15 mm		
	C	8-12 mm	8-12 mm			
	D	40-60 mm	40-60 mm			
thickness	**A**	1.5 m	1.5 m	1 m		
	B	The remainder	The remainder	The remainder		
	C	The remainder	The remainder			
	D	1.5 m	1.5 m			

Vegetation					
Cell number	**1**	**2**	**3**	**4**	**5**
Species	*Phragmites*	*Phragmites*	*Phragmites*		
Plantation density	4 plants/m^2	4 plants/m^2	4 plants/m^2		
Plantation system	Plants	Plants	Plants		

Distribution systems and wastewater collection					
Cell number	**1**	**2**	**3**	**4**	**5**
Inlet *	Corrugated tube	Corrugated tube	Pebble wall		
Outlet *	Corrugated tube	Corrugated tube	Corrugated tube		
Between cells	Gravity	Gravity	Gravity		
By pass	Yes, there is a *by pass* from the outlet of the Imhoff tank, after the second pond and the outlet of the HSCW, always to the receiving media.				

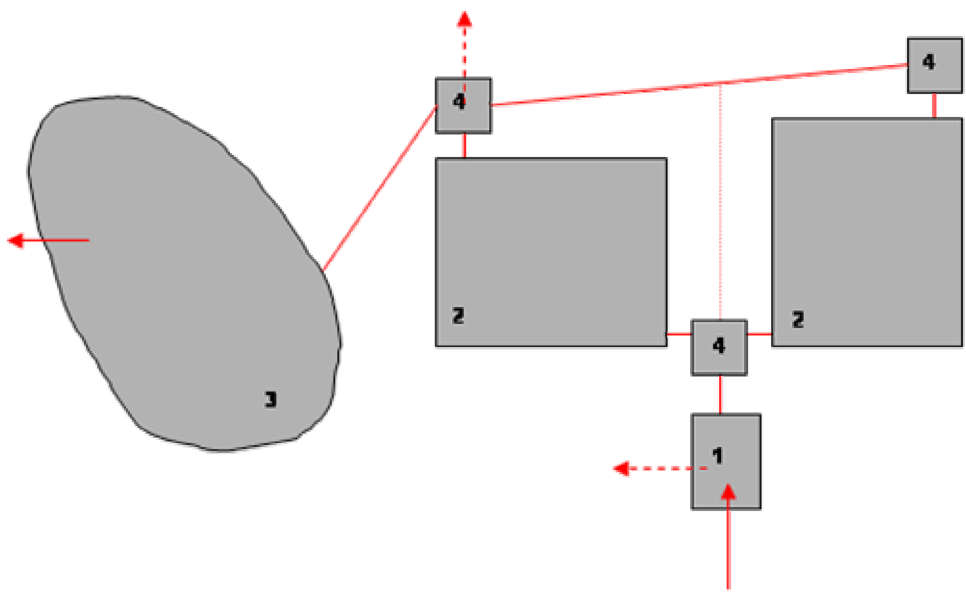
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.24. Summary file of maintenance carried out in the HSCWS of *Corbins*.

Visits to the WWTP
Frequency: 3-4 visits per week **Description:** The pre-treatment system (grid) is cleaned, the holes in the distribution tubes are checked for blockages, and the state of the cells is checked. Herbicide is also applied to the weeds growing on the paths.
Vegetation control
Cutting frequency (season): Twice a year (spring-winter) **What happens to the debris?** It is taken to the tip. **Weed removal:** Weeds are removed manually after the cutting period when it is easiest. Those growing on the edges are pulled up as soon as they are detected. **Treatment of diseases/fungal infections/others:** At the end of August a white grub was detected which eats *Phragmites australis*, and the plant turns yellow. As cutting was soon to be carried out, this procedure was implemented and the plague was eliminated.
Insects
When were they detected? / **Treatment of the problem:** /
Rodents
When were they detected? Damage caused by field mice (*Apodemus sylvaticum*) has been noted on the waterproof layer. **Treatment of the problem:** Rat poison has been applied around the cells.
Water level
Surface flux: The two cells have a free surface flux on 15% of their surface which is caused by the poor functioning of the water distribution tubes (blocked holes). **Actions carried out:** The tube was uncovered and the holes are now located pointing upwards. Coarse gravel has also been added to the first 1.5 m in order to avoid clogging in this zone. **Why and when the water level varies:** Two days before cutting the water level is lowered in order to avoid damage caused by cutting machinery. **Degree of variation:** The water level is lowered to minimum levels.
Bad smells
No important occurrences of bad smells have been detected.
Distribution systems
What problems occur? The holes in the distribution tubes become blocked **How are the problems solved?** The holes are unblocked during routine visits to the plant. In addition, once a month, water is hosed through the tube in order to clean the inner surfaces.
Waterproofing
The waterproof layer has been damaged by holes made by small rodents.

Table A1.25. Inventory for the HSCW of *Gualba*.

Community	
Community	*Gualba*
Region	*Vallès Oriental*
Year of construction/Initial operations	2002
WWTP configuration	
Pre-treatment	Thick and fine screen
Primary	/
Secondary	HSCW
Tertiary	Waste stabilization pond
Diagram	



1. Inlet and pre-treatment; **2.** HSCW; **3.** Pond; **4.** Wastewater distributor
Water conducts, *By pass* and Change series /parallel

Parcel	
Distance to community	300 m
Distance to receiving media	30 m
Parcel area	8,192 m^2
Distance to trees and/or bushes	10 m
Altitude above sea level	177 m
Electricity	Yes
Perimeter fence	Yes, wire, 2 m high with an access gate(2 x 4 m) 1 m from the cells (at the closest point)
Wastewater details	
Population	1,000 inhabitants
Seasonal population	1,224 inhabitants in summer
Industrial activity	Only a few restaurants

	Treated wastewater	
	Performances	***Outlet***
SS	54.45%	41 mg/l
BOD_5	73.96%	36 mg/l
COD	55.09%	125 mg/l

Table A1.26. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *Gualba*.

Pre-treatment

Description

Thick screen: Metal grid, manually cleaned with an opening of 3 – 4 cm.
Fine screen: Vertical sieve with a 2-3 mm opening.

Diagram or photograph

Thick screen

Fine screen

Primary treatment

Description

/

Diagram or photograph

Tertiary treatment

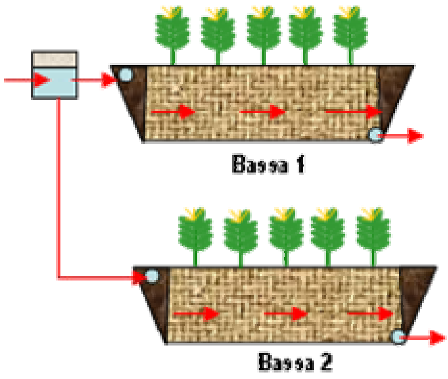
Description

Finishing pond with a surface area of 2,600 m^2 and an approximate depth of 1m. This year it is not in use due to problems of bad smells, suspended solids the effluent, etc.

Diagram or photograph

Table A1.27. Design of the HSCW of *Gualba*.

Diagram of the HSCW



Characteristics of the cells					
Cell number	**1**	**2**	**3**	**4**	**5**
Length	26.5 m	26.5 m			
Width	50.5 m	50.5 m			
Depth *	0.36 m	0.36 m			
Base inclination *	1%	1%			
Interior dike inclination *					
Exterior dike inclination *	Land-based cells	Land-based cells			
Safety margin *	30-40 cm	30-40 cm			
Covering*	/	/			
Waterproofing	Membrane	Membrane			
Matrix *					
diameter **A**	40-60 mm	40-60 mm			
diameter **B**	8-12 mm	8-12 mm			
diameter **C**	40-60 mm	40-60 mm			
thickness **A**	1 m	1 m			
thickness **B**	The remainder	The remainder			
thickness **C**	1 m	1 m			
Vegetation					
Cell number	**1**	**2**	**3**	**4**	**5**
Species	*Phragmites*	*Phragmites*			
Plantation density					
Plantation system	Plants	Plants			
Distribution systems and wastewater collection					
Cell number	**1**	**2**	**3**	**4**	**5**
Inlet *	Perforated tube	Perforated tube			
Outlet *	Corrugated tube	Corrugated tube			
Between cells	Gravity	Gravity			
By pass	Yes, from the pre-treatment and from the second cell to the receiving media.				

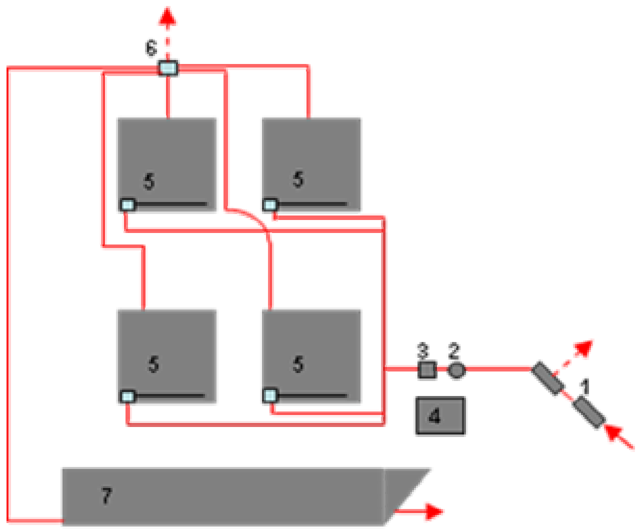
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.28. Summary file of maintenance carried out in the HSCW of *Gualba*.

Visits to the WWTP
Frequency: 1 visit per day **Description:** The pre-treatment system is cleaned and the cells and the outlet water are inspected to verify if the plant is operating correctly.
Vegetation Control
Cutting frequency (season): Once a year (winter) **What happens to the debris?** It is taken to be used as compost. **Weed removal:** The weeds which grow in the cells are not considered to be a problem for the treatment system and are therefore not removed. The paths are cut in order to keep the site in proper conditions. **Treatment of diseases/fungal infections/others:** /
Insects
When were they detected? / **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: Surface flux is present on the cells in the areas near the water inlet and in the lower part of the cell. **Actions carried out:** At present the actions to be taken are being investigated. **Why and when the water level varies:** The water level has been slightly reduced in order to avoid the accumulation of water in the lowest part of the cell. **Degree of variation:** /
Bad smells
Bad smells have occurred due to the accumulation of water in the lower part of the cells.
Distribution systems
What problems occur? Accumulation of solids inside the tubes. **How are the problems solved?** The holes are unblocked during routine visits to the plant. In addition, once a month, water is hosed through the tube in order to clean the inner surfaces.
Waterproofing
The waterproof layer shows no sign of defects.

Table A1.29. Inventory for the HSCW of *La Fatarella*.

Community	
Community	*La Fatarella*
Region	*Terra Alta*
Year of construction/Initial operations	1998/1999
WWTP configuration	
Pre-treatment	Thick screen and sand remover
Primary	Primary settling tank
Secondary	HSCW
Tertiary	Waste stabilization pond
Diagram	



1. Inlet and pre-treatment; **2.** Settling tank; **3.** Flow valves; **4.** Material shed; **5.** HSCW; **6.** Pumping; **7.** Waste stabilization pond
Water conducts and *By pass*

Parcel	
Distance to community	1,000 m
Distance to receiving media	5 m
Parcel area	7,000 m
Distance to trees and/or bushes	15 m
Altitude above sea level	200 m
Electricity	Yes
Perimeter fence	Yes
Wastewater details	
Population	1,200 inhabitants
Seasonal population	No
Industrial activity	No

Treated wastewater		
	Performances	***Outlet***
SS	33.24%	68.68 mg/l
BOD_5	77.78%	64.72 mg/l
COD	62.57%	195.32 mg/l

Table A1.30. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *La Fatarella*.

Pre-treatment

Description

Thick screen: Metal grid with mesh opening of 3 – 4 cm.
Sand remover: 0.8 x 0.8 m and 1 m deep.

Diagram or photograph

Primary treatment

Description

Primary settling tank: Concrete tank, 2.25 m in diameter and divided into two separate parts by a concrete funnel. Retention time is 14.26 minutes.

Diagram or photograph

Tertiary treatment

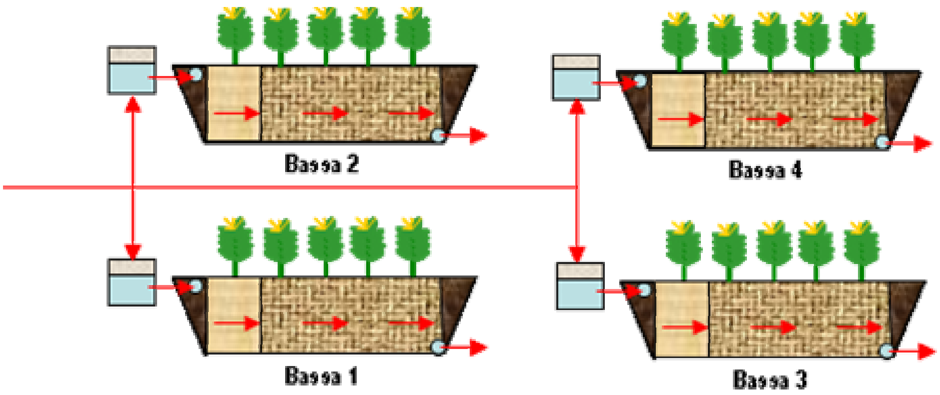
Description

Optional pond: Cell of 1.75 m deep with a surface area of 1,770 m^2. Retention time is 16 days.

Diagram or photograph

Table A1.31. Design of the HSCW of *La Fatarella*.

Diagram of the HSCW



Characteristics of the cells						
Cell number		**1**	**2**	**3**	**4**	**5**
Length		26 m	26 m	26 m	26 m	
Width		40 m	40 m	40 m	40 m	
Depth *		0.6 m	0.6 m	0.6 m	0.6 m	
Base inclination *		1%	1%	1%	1%	
Interior dike inclination *						
Exterior dike inclination *		Land-based cells	Land-based cells	Land-based cells	Land-based cells	
Safety margin *						
Covering*						
Waterproofing		Membrane	Membrane	Membrane	Membrane	
Matrix *						
diameter	**A**	10-100 mm	10-100 mm	10-100 mm	10-100 mm	
	B	2-10 mm	2-10 mm	2-10 mm	2-10 mm	
	C	10-100 mm	10-100 mm	10-100 mm	10-100 mm	
thickness	**A**	1 m	1 m	1 m	1 m	
	B	The remainder	The remainder	The remainder	The remainder	
	C	1 m	1 m	1 m	1 m	
Vegetation						
Cell number		**1**	**2**	**3**	**4**	**5**
Species		*Phragmites australis*	*Phragmites australis*	*Phragmites australis*	*Phragmites australis*	
Plantation density		4 plants/m^2	4 plants/m^2	4 plants/m^2	4 plants/m^2	
Plantation system		Plants	Plants	Plants	Plants	
Distribution systems and wastewater collection						
Cell number		**1**	**2**	**3**	**4**	**5**
Inlet *		Corrugated tube	Corrugated tube	Corrugated tube	Corrugated tube	
Outlet *		Corrugated tube	Corrugated tube	Corrugated tube	Corrugated tube	
Between cells		Gravity	Gravity	Gravity	Gravity	
By pass		At pre-treatment after sand removal and at the pumping point				

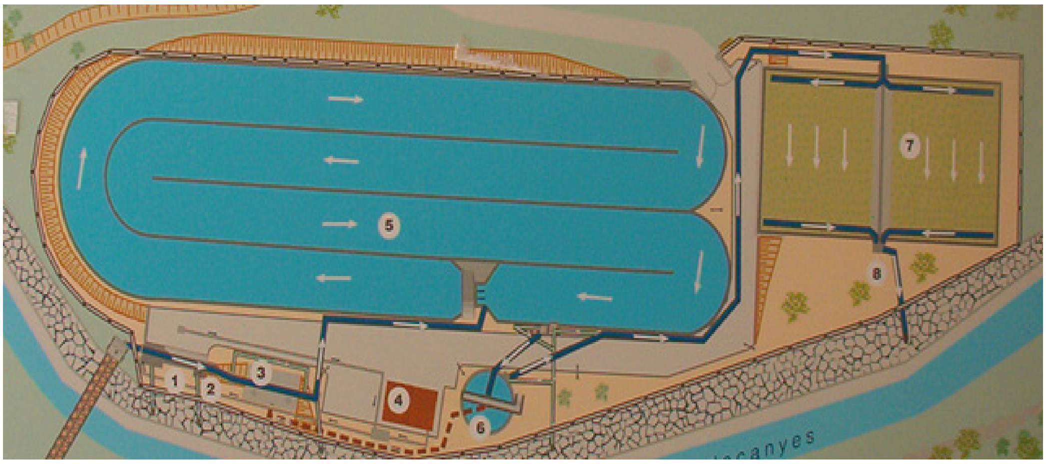
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.32. Summary file of maintenance carried out in the HSCW of *La Fatarella*.

Visits to the WWTP
Frequency: 1 visit per day **Description:** The pre-treatment system is cleaned and the cells are inspected to verify if the plant is operating correctly.
Vegetation control
Cutting frequency (season): Once a year (winter) **What happens to the debris?** It is burned in areas near the cells **Weed removal:** The weeds which grow in the cells are not considered to interfere in the treatment system and are therefore not removed. Those which grow on the paths are removed. **Treatment of diseases/fungal infections/others** /
Insects
When were they detected? Beehives have been detected in the area surrounding the site. **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: Free surface flux is present on 25% of the surface area of the 4 cells. There are crust formations. **Actions carried out:** There are several half-buried tubes on the surface which allow the water level to be observed (lysimeters). **Why and when the water level varies:** The water level is reduced before cutting is carried out. **Degree of variation:** Minimum level.
Bad smells
No important occurrences of bad smells have been detected
Distribution systems
What problems occur? The distribution system may become blocked. **How are the problems solved?** The distribution tubes are cleaned once every 3 months.
Waterproofing
The geotextile is damaged.

Table A1.33. Inventory for the HSCW of *Riudecanyes*.

Community		
Community	*Riudecanyes*	
Region	*Baix Camp*	
Year of construction/Initial operations	2000 – 2001	
WWTP configuration		
Pre-treatment	Thick screen and sand remover	
Primary	Imhoff tank	
Secondary	High rate pond + Secondary settling tank	
Tertiary	HSCW	
Diagram		



1. Pre-treatment; **2.** Flowmeters; **3.** Imhoff tank; **4.** Control building; **5.** High rate pond; **6.** Secondary settling tank; **7.** Constructed wetlands; **8**. Outlet

Parcel		
Distance to community	1,000 m	
Distance to receiving media	3-4 m	
Parcel area	12,000 m^2	
Distance to trees and/or bushes	There are no trees	
Altitude above sea level	600 m	
Electricity	Yes	
Perimeter fence	Yes, wire, 2 m high with an access gate(2 x 6 m) 10 m from the cells	
Wastewater details		
Population	900 inhabitants	
Seasonal population	1,200 inhabitants in summer	
Industrial activity	Oil production plant	
Treated wastewater		
	Performances	***Outlet***
SS	69.24%	98 mg/l
BOD_5	87.02%	70 mg/l
COD	77. 38%	235 mg/l

Table A1.34. Design of the pre-treatment, primary treatment and secondary treatment of the HSCW of *Riudecanyes*.

Pre-treatment

Description

Thick screen: Worm gear and metal grid with 4 mm mesh opening, manually cleaned. The grid is only used when the screw does not function.
Sand-remover: Well of 2 m x 1m, located in front of the large-scale material refiner.

Diagram or photograph


Thick screen


Worm gear

Primary treatment

Description

Imhoff tank: 10 m wide, 5 m long and 8 m deep. Half-buried.

Diagram or photograph

Secondary treatment

Description

High rate pond with concrete wall and covered with a black membrane. 112 m long, 37 m wide and 70 cm deep.
Secondary settling tank 4-5 m in diameter.

Diagram or photograph


High rate pond

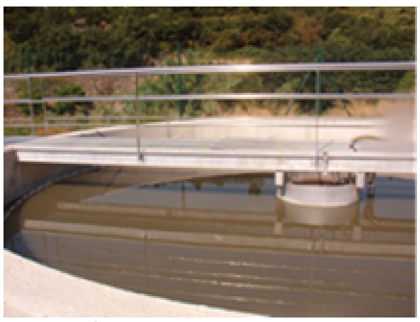
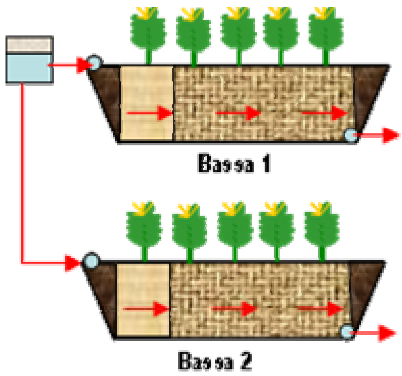

Secondary settling tank

Table A1.35. Design of the HSCW of *Riudecanyes*.

Diagram of the HSCW



Characteristics of the cells					
Cell number	**1**	**2**	**3**	**4**	**5**
Length	50 m	50 m			
Width	25 m	25 m			
Depth *					
Base inclination *					
Interior dike inclination *					
Exterior dike inclination *	Land-based cells	Land-based cells			
Safety margin *	40 cm	40 cm			
Covering*	/	/			
Waterproofing	Membrane	Membrane			
Matrix *					
diameter **A**	12-20 mm	12-20 mm			
diameter **B**					
diameter **C**					
thickness **A**	All the base	All the base			
thickness **B**					
thickness **C**					
Vegetation					
Cell number	**1**	**2**	**3**	**4**	**5**
Species	*Phragmites*	*Phragmites*			
Plantation density	2,000 plants between the 2 cells				
Plantation system					
Distribution systems and wastewater collection					
Cell number	**1**	**2**	**3**	**4**	**5**
Inlet *	Perforated tube	Perforated tube			
Outlet *	Corrugated tube	Corrugated tube			
Between cells	Gravity	Gravity			
By pass	Yes, after the Imhoff tank and the sand remover to the river, and the Imhoff tank to the secondary settling tank (provisional).				

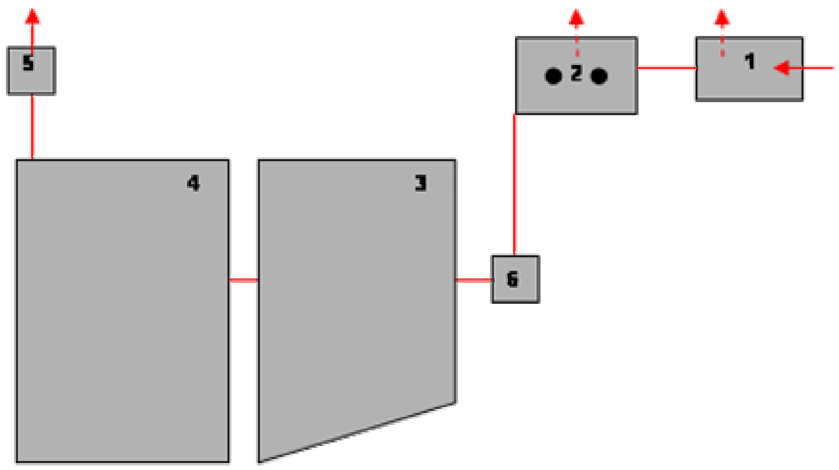
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.36 Summary file of maintenance carried out in the HSCW of *Riudecanyes*.

Visits to the WWTP
Frequency: 1 visit per day **Description:** The maintenance cells are centred on the pre-treatment and primary treatment system. The maintenance of the constructed wetland is minimal as at present they are not operational.
Vegetation control
Cutting frequency (season): / **What happens to the debris?** / **Weed removal:** Weed removal from the paths is the only task undertaken. **Treatment of diseases/fungal infections/others:** /
Insects
When were they detected? / **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: / **Actions carried out:** / **Why and when the water level varies:** The water is only fed to the HSCW from time to time in order to ensure that the reeds do not die. **Degree of variation:** /
Bad smells
No important occurrences of bad smells have been reported.
Distribution systems
What problems occur? / **How are the problems solved?** /
Waterproofing
The waterproof layer does not show any sign of defects.

Table A1.37 Inventory for the HSCW *Sant Martí Sesgueioles*.

Community	
Community	*Sant Martí Sesgueioles*
Region	*Anoia*
Year of construction/Initial operations	2001
WWTP configuration	
Pre-treatment	Thick and fine screen
Primary	Septic tank
Secondary	HSCW
Tertiary	/
Diagram	



1. Inlet and pre-treatment; **2.** Septic tank; **3** and **4.** HSCW; **5.** Outlet; **6.** Wastewater distributor
Water conducts and *By pass*

Parcel		
Distance to community	400 m	
Distance to receiving media	20-30 m	
Parcel area	9,239 m^2	
Distance to trees and/or bushes	5-10 m	
Altitude above sea level	646 m	
Electricity	No	
Perimeter fence	Yes, wire, 2 m high with an access gate (2 x 4.40 m) 2 m from the cells.	
Wastewater details		
Population	360 inhabitants	
Seasonal population	500 inhabitants in summer	
Industrial activity	Municipal abattoir	
Treated wastewater		
	Performances	***Outlet***
SS	93.14%	16 mg/l
BOD_5	83.50%	31 mg/l
COD	77.86%	113 mg/l

Table A1.38. Design of the pre-treatment, primary treatment and tertiary treatment of the HSCW of *Sant Martí Sesgueioles*.

Pre-treatment

Description

Thick screen: Metal grid with a 4 cm opening, manually cleaned.
Fine screen: Metal grid with a 1-1.5 cm opening, manually cleaned

Diagram or photograph

Primary treatment

Description

Septic tank of approximately 20,000 litre capacity.

Diagram or photograph

Tertiary treatment

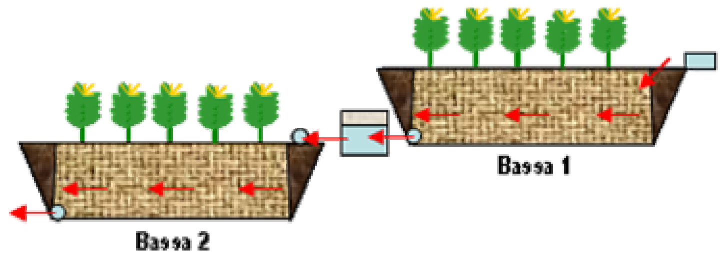
Description

/

Diagram or photograph

Table A1.39. Design of the HSCWS of *Sant Martí Sesgueioles*.

Diagram of the HSCW



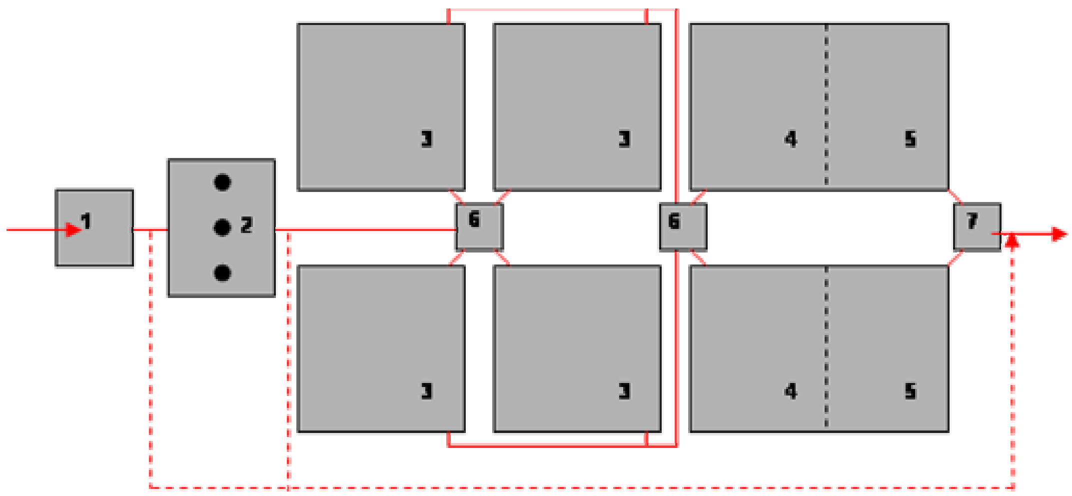
Characteristics of the cells						
Cell number		1	2	3	4	5
Length		22 m	37.4-11 m			
Width		19 m	46 m			
Depth *		0.6-0.93 m	0.6-0.9 m			
Base inclination *		1.5%	1.5%			
Interior dike inclination *		50%	50%			
Exterior dike inclination *		Land-based cells	Land-based cells			
Safety margin *		20-25 cm	20-25 cm			
Covering*		/	/			
Waterproofing		Membrane	Membrane			
Matrix *						
diameter	**A**	50-100 mm	50-100 mm			
	B	3-10 mm	3-10 mm			
	C	50-100 mm	50-100 mm			
thickness	**A**	50 cm	50 cm			
	B	The remainder	The remainder			
	C	50 cm	50 cm			
Vegetation						
Cell number		1	2	3	4	5
Species		*Phragmites*	*Phragmites*			
Plantation density		4 plants/m^2	4 plants/m^2			
Plantation system		Plants	Plants			
Distribution systems and wastewater collection						
Cell number		1	2	3	4	5
Inlet *		Channel	Perforated tube			
Outlet *		Gravel bed	Gravel bed			
Between cells		Gravity	Gravity			
By pass		Yes, at refinement and at the septic tank, to the receiving media.				

* For more information on these characteristics see the Glossary at the end of ANNEX I.

OBSERVATION: The part of this questionnaire which refers to use and maintenance could not be carried out in *Sant Martí Sesgueioles*, the final table for this WWTP has there fore been omitted.

Table A1.40. Inventory for the HSCW of *Verdú*.

Community	
Community	*Verdú*
Region	*Urgell*
Year of construction/Initial operations	2001 - 2002
WWTP configuration	
Pre-treatment	Thick screen
Primary	Septic tank
Secondary	HSCW
Tertiary	Waste stabilization pond + HSCW
Diagram	



1. Inlet and pre-treatment; **2.** Septic tank; **3.** HSCW; **4.** Pond; **5**. HSCW;
6. Wastewater distributor; **7.** Outlet
Water conducts and *By pass*

Parcel	
Distance to community	2,000 m
Distance to receiving media	600 m
Parcel area	20,000 m^2
Distance to trees and/or bushes	There are no trees or shrubs
Altitude above sea level	434 m
Electricity	No
Perimeter fence	Yes, wire, 2 m high with an access gate(2 x 4 m) 3 m from the cells
Wastewater details	
Population	1,000 inhabitants
Seasonal population	2,000 inhabitants in summer and 200 inhabitants at weekends
Industrial activity	Ceramics

	Treated wastewater	
	Yields	***Outlet***
SS	73.62%	34 mg/l
BOD_5	92.93%	13 mg/l
COD	76.82%	86 mg/l

Table A1.41. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *Verdú*.

Pre-treatment

Description

Thick screen: Metal grid, manually cleaned with 4cm mesh opening.

Diagram or photograph

Primary treatment

Description

Septic tank: Three septic tank units with capacity for 50,000 l each.

Diagram or photograph

Tertiary treatment

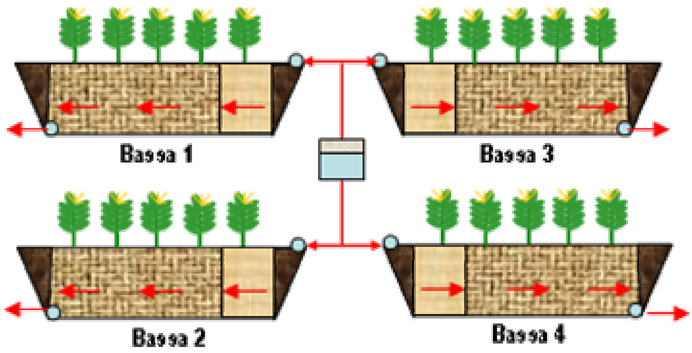
Description

Waste stabilization pond: 1 m deep with a surface area of 1,000 m^2. After these ponds there is a HSCW.

Diagram or photograph

Table A1.42. Design of the HSCW of *Verdú*.

Diagram of the HSCW



Characteristics of the cells					
Cell number	**1**	**2**	**3**	**4**	**5**
Length	36 m	36 m	36 m	36 m	
Width	35 m	35 m	35 m	35 m	
Depth *	0.8 m	0.8 m	0.8 m	0.8 m	
Base inclination *	2%	2%	2%	2%	
Interior dike inclination *	1%	1%	1%	1%	
Exterior dike inclination *	Land-based cells	Land-based cells	Land-based cells	Land-based cells	
Safety margin *	1-2 cm	1-2 cm	1-2 cm	1-2 cm	
Covering*	/	/	/	/	
Waterproofing	Membrane	Membrane	Membrane	Membrane	
Matrix *					
diameter **A**	40-60 mm	40-60 mm	40-60 mm	40-60 mm	
diameter **B**	8-12 mm	8-12 mm	8-12 mm	8-12 mm	
diameter **C**	40-60 mm	40-60 mm	40-60 mm	40-60 mm	
thickness **A**	1 m	1 m	1 m	1 m	
thickness **B**	The remainder	The remainder	The remainder	The remainder	
thickness **C**	0.5 m	0.5 m	0.5 m	0.5 m	
Vegetation					
Cell number	**1**	**2**	**3**	**4**	**5**
Species	*Phragmites*	*Phragmites*	*Phragmites*	*Phragmites*	
Plantation density	4 plants/m^2	4 plants/m^2	4 plants/m^2	4 plants/m^2	
Plantation system	Plants	Plants	Plants	Plants	
Distribution systems and wastewater collection					
Cell number	**1**	**2**	**3**	**4**	**5**
Inlet *	Perforated tube	Perforated tube	Perforated tube	Perforated tube	
Outlet *	Corrugated tube	Corrugated tube	Corrugated tube	Corrugated tube	
Between cells	Gravity	Gravity	Gravity	Gravity	
By pass	Yes, one to the inlet and another to the outlet of the septic tank, both to the outlet.				

* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.43. Summary file of maintenance carried out in the HSCW of *Verdú*.

Visits to the WWTP
Frequency: 2-3 visits per week **Description:** The pre-treatment system (grid) is cleaned, the distribution tubes are checked for blockages, and the state of the cells is checked. Herbicide is also applied to the weeds growing on the paths.
Vegetation control
Cutting frequency (season): Twice a year (spring-winter) **What happens to the debris?** The debris is placed on adjacent land and left to dry. **Weed removal:** Weeds are removed manually after cutting, when removal is easiest. Those growing on the edges of the plant are pulled up as soon as they are detected. **Treatment of diseases/fungal infections/others:** /
Insects
When were they detected? / **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: Surface flux occurs in the first metres of the cells. **Actions carried out:** The tube was uncovered and the holes are now pointing upwards. Coarse gravel has also been added to the first 1.5 m in order to avoid clogging in this area. **Why and when the water level varies:** Before the cutting period the water level is reduced to a minimum level in order to avoid the cutting machinery damaging the cells. **Degree of variation:** Minimum level.
Bad smells
No important occurrences of bad smells have been detected
Distribution systems
What problems occur? Blocking of the holes in the distribution tubes due to the accumulation of solids inside. **How are the problems solved?** The holes are unblocked during routine visits to the plant. In addition, once a month, water is hosed through the tube in order to clean the inner surfaces.
Waterproofing
The waterproof layer does not show signs of defects.

Table A1.44. Inventory for the HSCW of *Vilajuïga*.

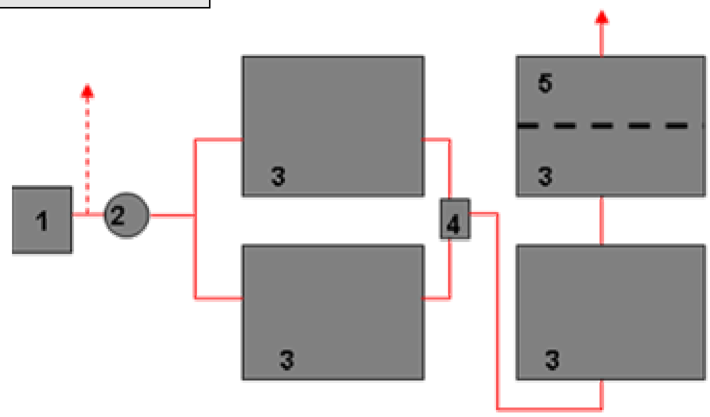
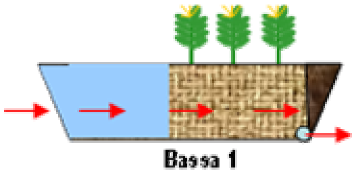
Community		
Community	*Vilajuïga*	
Region	*Alt Empordà*	
Year of construction/Initial operations	1998	
WWTP configuration		
Pre-treatment	Thick and fine screen	
Primary	Primary settling tank	
Secondary	Waste stabilization pond	
Tertiary	HSCW	
Diagram	**1.** Pre-treatment; **2.** Primary settling tank; **3.** Pond; **4.** Wastewater distributor; **5.** HSCW Water conducts and *By pass*	
Parcel		
Distance to community	1,000 m	
Distance to receiving media	/	
Parcel area	/	
Distance to trees and/or bushes	15 m	
Altitude above sea level	31 m	
Electricity	Yes	
Perimeter fence	Yes	
Wastewater details		
Population	900 inhabitants	
Seasonal population	No	
Industrial activity	No	
Treated wastewater		
	Performances	***Outlet***
SS	/	/
BOD_5	/	/
COD	/	/

Table A1.45. Design of pre-treatment, primary treatment and tertiary treatment of the HSCWS of *Vilajuïga*.

Pre-treatment
Description Thick screen: Large-scale material grid with a mesh opening of 3-4 cm. Fine screen: Small-scale material sieve and compactor.
Diagram or photograph
Primary treatment
Description Primary settling tank
Diagram or photograph
Tertiary treatment
Description Waste stabilization pond: 2 optional ponds which function in parallel, and a third pond. All are waterproofed with 30 cm of compacted clay.
Diagram or photograph 

Table A1.46. Design of the HSCW of *Vilajuïga*.

Diagram of the HSCW



Characteristics of the cells					
Cell number	**1**	**2**	**3**	**4**	**5**
Length					
Width					
Depth *					
Base inclination *					
Interior dike inclination *					
Exterior dike inclination *	Land-based cell				
Safety margin *					
Covering*					
Waterproofing	No				
Matrix *					
diameter **A**					
diameter **B**					
diameter **C**					
thickness **A**					
thickness **B**					
thickness **C**					
Vegetation					
Cell number	**1**	**2**	**3**	**4**	**5**
Species	*Phragmites* and *Scirpus*				
Plantation density					
Plantation system					
Distribution systems and wastewater collection					
Cell number	**1**	**2**	**3**	**4**	**5**
Inlet *	Rock wall				
Outlet *					
Between cells					
By pass	A *by pass* is fitted after the water inlet.				

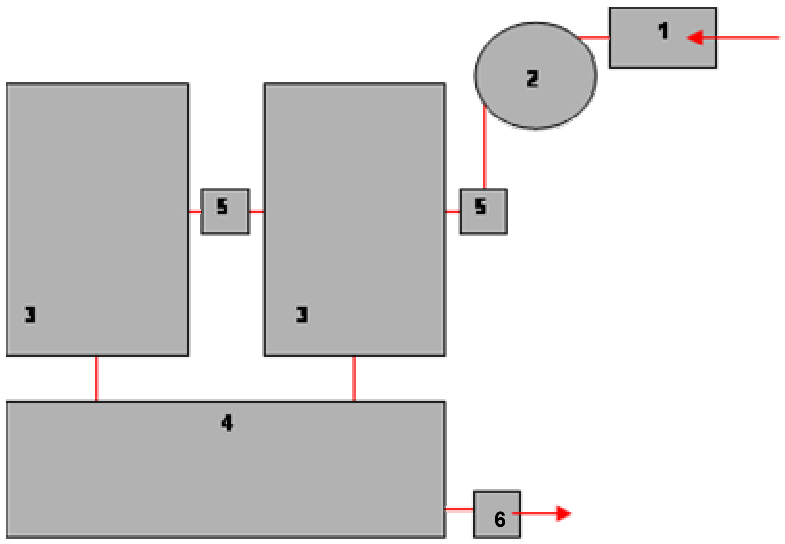
* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.47. Summary file of maintenance carried out in the HSCWS of *Vilajuïga*.

Visits to the WWTP
Frequency: 3-4 visits per week **Description:** Each week an hour is spent cleaning the pre-treatment system, and all system components are checked to ensure that they function correctly.
Vegetation control
Cutting frequency (season): Cutting is not carried out. **What happens to the debris?** / **Weed removal:** The weeds which grow on the paths are eliminated through the use of herbicides. **Treatment of diseases/fungal infections/others** /
Insects
When were they detected? / **Treatment of the problem:** /
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: Although the constructed wetland is an HSCW, there is surface flux. **Actions carried out:** / **Why and when the water level varies:** The water level increases or diminishes with regard to the state of the cells through the inlet sluice gate. **Degree of variation:** /
Bad smells
No important occurrences of bad smells have been detected
Distribution systems
What problems occur? The water enters the HSCW through a stone wall and flows on the surface. **How are the problems solved?** /
Waterproofing
/

Table A1.48. Inventory for the HSCW of *Vilaplana*.

Community	
Community	*Vilaplana*
Region	*Baix Camp*
Year of construction/Initial operations	2001
WWTP configuration	
Pre-treatment	Fine screen
Primary	Primary settling tank
Secondary	HSCW
Tertiary	Plant soil treatment
Diagram	



1. Inlet and pre-treatment; **2.** Primary settling tank; **3.** HSCW; **4.** Plant soil treatment; **5.** Wastewater distributor; **6.** Outlet

Parcel	
Distance to community	600 m
Distance to receiving media	< 100 m
Parcel area	4,000 m^2
Distance to trees and/or bushes	3 m
Altitude above sea level	364 m
Electricity	No
Perimeter fence	Yes, wire, 2 m high with an access gate(2 x 3 m) 3 m from the cells
Wastewater details	
Population	800 inhabitants
Seasonal population	1,000 inhabitants in summer
Industrial activity	Stables with 15-20 horses

Treated wastewater		
	Performances	***Outlet***
SS	92.32%	19 mg/l
BOD_5	84.92%	48 mg/l
COD	85.21%	115 mg/l

Table A1.49. Design of pre-treatment, primary treatment and tertiary treatment of the HSCW of *Vilaplana*.

Pre-treatment

Description

Fine screen: Vertical, self-cleaning sieve with a 5 mm mesh opening.

Diagram or photograph

Primary treatment

Description

Primary settling tank: 3 m deep and 2 m in diameter.

Diagram or photograph

Tertiary treatment

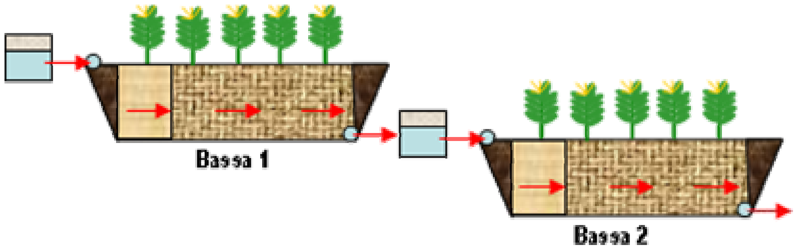
Description

Plant soil treatment: Poplar grove of approx. 50 trees.

Diagram or photograph

Table A1.50. Design of the HSCW of *Vilaplana*.

Diagram of the HSCW



Characteristics of the cells						
Cell number		1	2	3	4	5
Length		50 m	50 m			
Width		50 m	50 m			
Depth *						
Base inclination *						
Interior dike inclination *						
Exterior dike inclination *		Land-based cells	Land-based cells			
Safety margin *		40 cm	40 cm			
Covering*		/	/			
Waterproofing		Membrane	Membrane			
Matrix *						
diameter	**A**	40-60 mm	40-60 mm			
	B	8-12 mm	8-12 mm			
	C	40-60 mm	40-60 mm			
thickness	**A**	1.5 m	1.5 m			
	B	The remainder	The remainder			
	C	1.5 m	1.5 m			

Vegetation					
Cell number	1	2	3	4	5
Species	*Phragmites*	*Phragmites*			
Plantation density					
Plantation system	Plants	Plants			

Distribution systems and wastewater collection					
Cell number	1	2	3	4	5
Inlet *	Perforated tube	Perforated tube			
Outlet *	Corrugated tube	Corrugated tube			
Between cells	Gravity	Gravity			
By pass	There is no *by pass*				

* For more information on these characteristics see the Glossary at the end of ANNEX I.

Table A1.51. Summary file of maintenance carried out in the HSCW of *Vilaplana*.

Visits to the WWTP
Frequency: 1 visit per day **Description:** The pre-treatment system is cleaned and an inspection is made in order to detect any problems in the plant components.
Vegetation control
Cutting frequency (season): Once a year (winter) **What happens to the debris?** It is taken to the tip. **Weed removal:** The weeds which grow inside the cells are not removed as they are not considered to affect the performance of the system. **Treatment of diseases/fungal infections/others** /
Insects
When were they detected? At first mosquitoes were reported when there was an accumulation of solid materials from the vertical sieve. **Treatment of the problem:** The solid material collection system from pre-treatment was repaired.
Rodents
When were they detected? / **Treatment of the problem:** /
Water level
Surface flux: The cells have free surface flux on 20% of their surface area, caused by blocked distribution tubes and the maintenance tasks of the green filters. **Actions carried out:** / **Why and when the water level varies:** When maintenance is carried out on the plant soil treatment the water flow to the filters is shut off and the water level in the cells therefore increases. **Degree of variation:** /
Bad smells
Bad smells have occurred during the summer months.
Distribution systems
What problems occur? The tubes become blocked due to the accumulation of solid material. **How are the problems solved?** The tube is cleaned using a flux of water 3 times a year.
Waterproofing
The geotextile is damaged.

Glossary

- **Inlet:** The word inlet is used to describe the system of wastewater distribution to the head of the cells. In this study there are three types of inlets: Constructed channel (Figure A1.1), corrugated tube (Figure A1.2) and perforated tube (Figure A1.3).

Figure A1.1. Photographs of the different constructed channels for water distribution to the inlet.

Figure A1.2. Photograph of a corrugated tube for water distribution to the inlet.

Figure A1.3. Photograph of the different perforated tubes for water distribution to the inlet.

- **Safety margin:** The distance from the crown of the dike to the surface of the matrix (Figure A1.4).

Figure A1.4. The red arrows indicate the concept of the safety margin.

- **Base inclination of the cells:** The base of the HSCW cells are constructed with a gradient of 0.5 – 2.0%, in order to facilitate the flow of water (Figure A1.5).

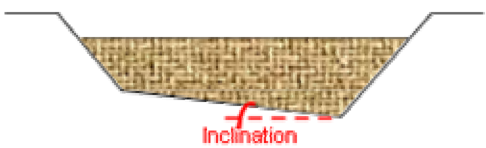


Figure A1.5. Diagram to show the concept of the inclination in the base of the HSCW cells. The red lines show the slope.

- **External inclination of the cell dikes:** The walls of the HSCW cells are constructed with a slope of 45-70% (highly variable, and dependent on the designer) (Figure A1.6).

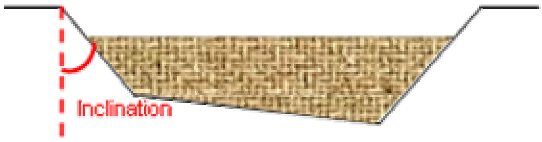


Figure A1.6. Diagram to show the concept of the exterior inclination in the HSCW cells.
The red lines show the slope.

- **Depth of the cells:** The distance from the crown to the base of the cell, measured in the shallowest part of the cell (Figure A1.7).

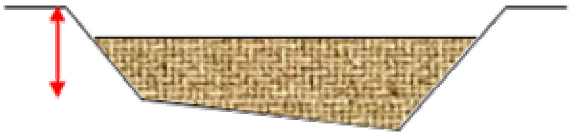


Figure A1.7 Diagram to show the concept of the depth of an HSCW.
The red arrow shows the depth.

- **Covering:** When the cells are not buried the dikes are covered with grass, gravel, concrete, membrane, etc.

- **Matrix:** The cells are filled with gravel of different granule size. The diameter of the different types of gravels is specified in the matrix, in addition to the thickness of each of the different gravel layers.

- **Outlet:** The word outlet is used to describe the wastewater distribution system at the end of the cells. There is normally a margin of coarse gravel at the end of the cells, which surrounds a corrugated tube through which the water is collected. In some cases the cell has a double inclination (lengthways and sideways) so that the collection of treated water can be carried out easily without the need for a corrugated tube. In this case the term “gravel bed” is used.

Annex II - Glossary

Annex II - Glossary

List of problems

P1: Problem 1 - Abnormal vegetation growth during the start-up

P2: Problem 2 - Low density or non-homogeneous density of vegetation

P3: Problem 3 - Accumulation of plant debris in the HSCW area

P4: Problem 4 - Growth of weeds in the HSCW

P5: Problem 5 - Growth of trees and/or bushes in the HSCW area and/or the surrounding area

P6: Problem 6 - Chlorosis

P7: Problem 7 - Plague of rodents

P8: Problem 8 - Obstruction of the matrix pores and the clogging of the substrate

P9: Problem 9 - Water level too high – Formation of surface flow

P10: Problem 10 - Water level too low

P11: Problem 11 - Anomalies in the distribution systems and/or water collection

P12: Problem 12 - Anomalies in the water level controller mechanism

P13: Problem 13 - Anomalies in the waterproof layer

P14: Problem 14 - Anomalies in the dikes

P15: Problem 15 - Anomalies in the perimeter fence and the gate

P16: Problem 16 - Production of bad smells

P17: Problem 17 - High concentration of organic matter in the effluent

P18: Problem 18 - High concentration of suspended solids in the effluent

List of effects

E1: Effect 1 - Non-homogeneous water distribution

E2: Effect 2 -Reduction of the hydraulic retention time

E3: Effect 3 - Yellowing of the leaves of *Phragmites australis*, followed by leaf loss and the death of the plant

E4: Effect 4 - Reduction of the oxygen diffusion from the atmosphere to the radical area in the inside of the matrix

E5: Effect 5 - Presence of mosquitoes

E6: Effect 6 - Health risks for people who may enter into contact with the waste water

E7: Effect 7 - The roots dry out

E8: Effect 8 - Filtration into the subsoil

E9: Effect 9 - Entrance of water from the subsoil

E10: Effect 10 - Non-contention of the gravel bed and the wastewater which flows through the matrix

E11: Effect 11 - Entrance of groundwater

E12: Effect 12 - Entrance of people into the treatment system

E13: Effect 13 - Presence of animals which may damage the plants and structural components

E14: Effect 14 - Production of bad smells

E15: Effect 15 - Deoxygenation of the receiving media

E16: Effect 16 - Contamination of the subsoil and/or aquifers with organic matter.

E17: Effect 17 - Cloudiness of the receiving media (river, stream, natural pond, etc.)

E18: Effect 18 - Clogging of the receiving media (soil)

List of causes

C1: Cause 1 - Organic overload

C2: Cause 2 - Low temperature

C3: Cause 3 - High temperature

C4: Cause 4 - High evapotranspiration

C5: Cause 5 - Heavy rainfall

C6: Cause 6 - Strong gusts of wind

C7: Cause 7 - Density of plantation inferior to that recommended

C8: Cause 8 - Non-removal of plant biomass which falls naturally onto the HSCW

C9: Cause 9 - Plants transported with soil

C10: Cause 10 - Inadequate maintenance of the vegetation in the surroundings of the HSCW

C11: Cause 11 - Inadequate maintenance of the HSCW plant cover

C12: Cause 12 - Inadequate maintenance of the vegetation around the HSCW area

C13: Cause 13 - Low organic load

C14: Cause 14 - Lack of nutrients

C15: Cause 15 - Poorly developed rhizomes

C16: Cause 16 - Characteristics of the HSCW

C17: Cause 17 - Inadequate design of the dikes – Slope

C18: Cause 18 - Inadequate design of the dikes – Protection

C19: Cause 19 - Accumulation of debris in the HSCW surrounding area

C20: Cause 20 - Accumulation of suspended solids

C21: Cause 21 - Matrix with small diameter pores

C22: Cause 22 - Accumulation of plant debris in the HSCW surrounding area

C23: Cause 23 - Depth of the cells

C24: Cause 24 - The growth of micro-organisms

C25: Cause 25 - Chemical precipitation and deposition on the pores

C26: Cause 26 - Obstruction of the pores caused by the growth of rhizomes and roots

C27: Cause 27 - Accumulation of solids

C28: Cause 28 - Inadequate design and/or construction of the constructed channel

C29: Cause 29 - Formation of ice layers

C30: Cause 30 - Inadequate maintenance of the water level controller mechanism

C31: Cause 31 - Inadequate regulation of the water level controller mechanism

C32: Cause 32 - Non-compliance with the characteristics of the waterproof layer

C33: Cause 33 - Drying of the waterproof membrane

C34: Cause 34 - Use of machinery

C35: Cause 35 - Erosion of the soil

C36: Cause 36 - The growth of tress, bushes or weeds near the fence

List of measures

M1: Measure 1 - Visual control of the vegetation to verify the state of the planted macrophytes

M2: Measure 2 - Measure the concentration of organic matter (BOD5) in the influent

M3: Measure 3 - Measure the influent flow rate

M4: Measure 4 - Measure the temperature

M5: Measure 5 - Measure the water level

M6: Measure 6 - Measure the evapotranspiration

M7: Measure 7 - Measure the rainfall

M8: Measure 8 - Measure the wind (intensity and direction)

M9: Measure 9 - Visual control of the HSCW surface to verify whether there is accumulation of vegetation debris

M10: Measure 10 - Visual control of the HSCW surface to verify whether there is growing of weeds

M11: Measure 11 - Visual control of the surrounding area of the HSCW to verify whether there is growing of weeds

M12: Measure 12 - Visual control of the surface and surrounding area of the HSCW to verify whether there is growing of trees and/or bushes

M13: Measure 13 - Visual control to verify the state of the vegetation cover of the HSCW

M14: Measure 14 - Visual control to verify whether there is chlorosis

M15: Measure 15 - Visual control of the HSCW to verify whether there are evidences of rodents

M16: Measure 16 - Check the slope of the dikes

M17: Measure 17 - Check if dikes are protected by layer of gravel or rocks

M18: Measures 18 - Visual control of the surrounding area of the HSCW to verify whether there is accumulation of debris

M19: Measure 19 - Visual control of the HSCW surface to verify whether the matrix is clogged

M20: Measure 20 - Visual control of the water level controller mechanism

M21: Measure 21 - Measure the concentration of suspended solids in the influent

M22: Measure 22 - Verify the gravel diameter

M23: Measure 23 - Verify the density of plantation

M24: Measure 24 - Visual control to verify the design and construction of the channel

M25: Measure 25 - Visual control of the HSCW surface to verify whether there is wastewater flow over the matrix

M26: Measure 26 - Visual control to check if ice has formed on the surface or inside the tubes

M27: Measure 27 - Measure the concentration of BOD_5 in the effluent

M28: Measure 28 - Visual control of tubes to verify whether the holes are clogged

M29: Measure 29 - Visual control of channels to verify whether there is accumulation of solids

M30: Measure 30 - Visual control to verify the state of the waterproof layer

M31: Measure 31 - Verify the characteristics of the waterproof layer

M32: Measure 32 - Verify whether heavy machinery or cutting tools have been used

M33: Measure 33 - Visual control to verify the state of the dikes

M34: Measure 34 - Verify the state of the fence and the access gate

M35: Measure 35 - Verify the formation of bad smells

M36: Measure 36 - Visual control of the surrounding area of the HSCW to verify the accumulation of debris

M37: Measure 37 - Verify the presence of mosquitoes

M38: Measure 38 - Measure the concentration of suspended solids in the effluent

M39: Measure 39 - Measure the COD in the effluent

List of actions

AC1: Action 1 - Dilution with clean water

AC2: Action 2 - Recirculation

AC3: Action 3 - Previous treatment

AC4: Action 4 - Other actions to promote the growth of *Phragmites australis*

AC5: Action 5 - Replanting the plant cover

AC6: Action 6 - Removing plant debris accumulated in the HSCW area

AC7: Action 7 - Removing invading plants

AC8: Action 8 - Cutting the plant cover surrounding the HSCW

AC9: Action 9 - Application of chemical products

AC10: Action 10 - Light flooding of the HSCW

AC11: Action 11 - Removing the trees and/or bushes which grow around and/or in the HSCW area

AC12: Action 12 - Plant cover on the dikes

AC13: Action 13 - Consulting a specialist

AC14: Action 14 - Applying iron-based composts

AC15: Action 15 - “Iron-efficient” plants

AC16: Action 16 - Promoting the development of the roots

AC17: Action 17 - Reducing the slope of the dikes

AC18: Action 18 - Providing the dikes with a layer of gravel or rocks

AC19: Action 19 - Avoiding the accumulation of debris in the HSCW surrounding area

AC20: Action 20 - Covering the burrows

AC21: Action 21 - Trap and poison campaigns

AC22: Action 22 - Fitting a wire net over the HSCW surface

AC24: Action 24 - Dosing the water intake

AC25: Action 25 - Raking

AC26: Action 26 - Replacing the substrate

AC27: Action 27 - Applying coarse gravel

AC28: Action 28 - Install lysimeters

AC29: Action 29 - Reducing the water level

AC30: Action 30 - Using the reserve cell

AC31: Action 31 - Increasing the water level

AC32: Action 32 - Cleaning the water distribution tubes

AC33: Action 33 - Improving the water distribution systems

AC34: Action 34 - Cleaning the water distribution channels

AC35: Action 35 - Restructuring the water distribution channel

AC36: Action 36 - Repairing or substituting the water level controller mechanism

AC37: Action 37 - Restructuring the compacted soil waterproof layer

AC38: Action 38 - Replacing the waterproof layer

AC39: Action 39 - Fitting a solar radiation protection layer

AC40: Action 40 - Patching the solar radiation protection layer

AC41: Action 41 - Patching the waterproof membrane

AC42: Action 42 - Choosing the appropriate machinery

AC43: Action 43 - Repairing the dikes

AC44: Action 44 - Repairing the perimeter fence and the access gate

AC45: Action 45 - Planting a tree screen

AC46: Action 46 - Increasing the hydraulic retention time

AC47: Action 47 - Carrying out an aerobic pre-treatment

AC48: Action 48 - Other actions to deal with low temperatures

AC49: Action 49 - Increasing the surface area of the treatment

AC50: Action 50 - Promoting the transference of oxygen

AC51: Action 51 - Provide a source of clean water

AC52: Action 52 - Install a recirculation device

AC53: Action 53 - Install a primary treatment

AC54: Action 54 - Install a water level controller

AC55: Action 55 - Install a mechanism to dosify wastewater

AC56: Action 56 - Cut the *Phragmites australis*

AC57: Action 57 - Install a fence

AC-P1: Apply the recommendations described for the P1

AC-P2: Apply the recommendations described for the P2

AC-P4: Apply the recommendations described for the P4

AC-P5: Apply the recommendations described for the P5

AC-P7: Apply the recommendations described for the P7

AC-P8: Apply the recommendations described for the P8

AC-P9: Apply the recommendations described for the P9

AC-P10: Apply the recommendations described for the P10

AC-P11: Apply the recommendations described for the P11

AC-P12: Apply the recommendations described for the P12

AC-P13: Apply the recommendations described for the P13

AC-P14: Apply the recommendations described for the P14

AC-P15: Apply the recommendations described for the P15