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PAPERS

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World Bank water supply and sanitation loan for Belarus

The World Bank has approved a $60 million loan to the Republic of Belarus for a water supply and sanitation project. This aims to increase the efficiency, quality and sustainability of water supply and sanitation services to 1.7 million people living in 20 rayons across the country. This is the first operation under the recently-approved World Bank's country assistance strategy for Belarus (2008 to 2011) which is targeted at areas that improve people's livelihoods and contribute to protecting the environment.

The project has three components. The first, with an allocation of $53.6 million, will finance water supply development through rehabilitation and construction of deep wells, pumping stations, transmission mains, distribution network, ground and elevated reservoirs and iron removal plants.

This component will also finance rehabilitation of the wastewater collection system and waste-water treatment plants including the installation of pumping stations, sludge dewatering systems, collection networks, monitoring stations and small laboratories.

The second component, worth $6.05 million, will finance engineering and construction management activities needed in order to undertake the investments in component one. These include engineering preparation, preparation of feasibility studies and designs as well as bidding documents. It will also include advisory services and construction supervision, as well as monitoring and evaluation and reporting on audits.

The third component, worth $0.2 million, will ensure project monitoring as well as training to enhance technical capacity and competence of the participating utilities.

The project will be implemented by a project coordinating team within the Republican Unitary Enterprise Zilkommuntekhnika reporting to the Ministry of Housing and Utilities.

EBRD supports water and wastewater projects in Siberia

The European Bank for Reconstruction and Development (EBRD) is supporting rehabilitation and upgrading of municipal district heating, water and wastewater services in the Siberian city of Pyt'Yakh with a 350 million rouble (equivalent to approximately €10 million) loan. A more efficient and effective use of resources will be central to the efforts.

The EBRD-financed programme will include a significant district heating focus, with water supply and wastewater collection facilities also being upgraded.

The municipal services management company that will be given the EBRD loan will implement the programme. The company is introducing a gradual tariff reform based on affordability, which will help set up sustainable business model.

Pyt'Yakh has around 40,000 inhabitants and is in the Khanty-Mansi Autonomous Okrug (region) in western Siberia. The city is about 200km west of one of the main cities of the region, Surgut, and was established in the 1960s following the discovery of western Siberia's second largest oil field.

The new EBRD loan is part of the Khanty-Mansi regional municipal services development programme, under which the bank has already provided two loans to Surgut for municipal services and housing refurbishment. Because of the success of the programme, other municipalities in the region are considering similar projects.

ADB and Japan provide grant for supply in Micronesia

Japan and the Asian Development Bank (ADB) are laying the foundations of a secure and safe water supply to residents of the capital of Chuuk, one of four of the Federated States of Micronesia (FSM). The Japanese Fund for Poverty Reduction (JFPR) is extending a $980,000 grant for the project, to be managed by FSM's Department of Transport, Communications and Infrastructure. The grant will support water demand forecasts for Weno Island up to 2020, identification of potential water sources to meet long-term demand, and a tariff study and survey to gauge the willingness of residents to pay for efficient water service.

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EDITORIAL

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Whole life cost optimisation model for water distribution systems: using modelling optimisation techniques to explore cost-effective mains rehabilitation in Kampala City, Uganda

As the assets in the ground continue to age, concern is growing about their continuing performance and the risks of future failure. Like most other utilities, water authorities must manage many aging capital assets that are in varying degrees of deterioration; some of which are nearing the end of their useful lives.

Rehabilitation and/or replacement of deteriorating pipe components demands huge sums of money from annual budgets of water utilities worldwide and yet the funds available for rehabilitation of these assets is limited. It is important therefore that the available funds are used in the most effective manner.

In order to ensure that the available funds are used in the most effective manner, it is important that their capital maintenance decisions not only reflect costs borne now but also the likely costs in the future, and how these can be optimised. This paper attempts to address the issue of optimal Whole Life Costing (WLC) rehabilitation and maintenance strategy of water distribution assets using genetic algorithm technique. The whole life cost approach for rehabilitation and maintenance of water distribution systems is aimed at optimising the present value of pipe replacement, repairs and cleaning costs over a defined analysis period while requirements for water standards are fulfilled.

The WLC analysis depicts a rehabilitation strategy over a defined analysis period together with the corresponding cost profile. H. Mutikanga, J. Sseguya and K. Vairavamoorthy use a case study in Kampala City, Uganda to demonstrate that the genetic algorithm can assist in planning of rehabilitation of water distribution systems.

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The cornerstone of any healthy population is access to safe drinking water. Because of the importance of safe drinking water for the needs of society and for industrial growth, considerable emphasis recently has been given to the condition of the infrastructure (Mays, 2000). The findings of several prominent

studies forecasting capital investment needs for water systems has brought the subject of buried infrastructure asset management to the forefront of priority issues facing the water industry (AWWSC, 2002).

Distribution networks often account for up to 80% of the total expenditure involved in water supply systems. As water mains deteriorate both structurally and functionally, their breakage rates increase, network hydraulic capacity decrease, and the water quality in the distribution system may deteriorate. Scarce capital resources make it essential for planners and decision makers to seek the most cost-effective rehabilitation and renewal strategy. The ideal strategy should exploit the full extent of the useful life of the individual pipe while addressing issues of safety, water quality and economic efficiency.

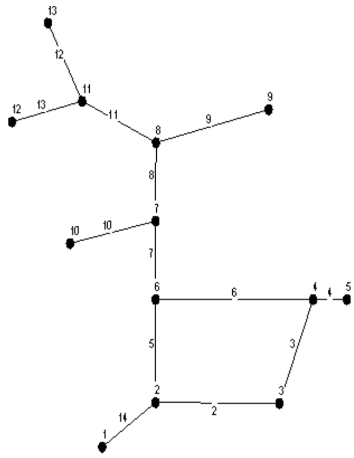
The efficient long-term management of large-scale public funded assets is therefore an area of growing importance. Ageing infra-structure, growth, and limited capital all result in the need for more robust and rigorous methodology to prioritise rehabilitation and renewal decisions and more importantly, to forecast future expenditure requirements (Watson et al, 1999). The study demonstrates the use of genetic algorithm technique to identify a near optimal rehabilitation strategy while considering the full extent of the useful life of the individual pipe. Genetic Algorithms have been successfully used in design of water distribution systems (Simpson et.al 1994; Dandy et.al 1996) and for optimal scheduling of water pipe replacement (Dandy and Engelhardt 2001).

This paper describes how the application of the whole life costing optimisation model has been applied to the distribution system in the city of Kampala in Uganda to facilitate the decision-making process in rehabilitation of water distribution systems. The approach does not only reflect the costs borne now but the likely costs in the future, and how these might be optimised. The whole life costing approach to the network management is very much desirable and aimed to achieve lowest network provision and operating cost when all costs are considered to meet regulatory standards.

The methodology described herein involves the application of whole life cost optimisation regarding rehabilitation of water distribution systems. The approach is presented as software and applied to a zone within the Kampala water distribution network to facilitate decision-making process in the management of system assets. For the case study, data requirements and pipe prediction models are presented, followed by the whole life cost rehabilitation framework that is subsequently optimised by the genetic algorithm (GA).

The outcome of the programme is presented, discussions made and conclusions drawn. Areas of possible future work are also highlighted.

Figure 1
Distribution network layout for Mbuya zone



Application of WLC to Mbuya zone in the Kampala distribution network

Kampala is the largest city in Uganda. It is the capital city and motor of the Ugandan economy. The service area encompasses an area of about 250 km^2. Population estimates based on 2002 National Census Data indicate that some 1.35 million inhabitants live in the service area with 1.21 million in the Kampala district. The annual growth rate since 1991 census is 3.8%. Daily water production is 130,000 m^3/day from three treatment plants in Gaba abstracting water from Lake Victoria. The distribution network comprises of about 1700 km of pipelines of varying sizes and materials; various reservoirs and booster stations.

The developed whole life cost optimisation model has been tested on Mbuya zone (Kampala water distribution system). The network has 13 pipes of steel and plastic pipes with diameters ranging between 100 – 40mm. It was not possible to consider a large section of the network because of the insufficient data and the non-existence of a 24-hour hydraulic model. Mbuya zone was considered because it was possible to isolate it from the entire network and build a small hydraulic model. The demands on the system were assigned based on the data from billing system for the block maps covering Mbuya zone. The major advantage of using a hydraulic model is that it reflects the distribution of demand throughout the system and ensures that the hydraulic performance of the system can be predicted fairly accurately. The network layout of the Mbuya zone is shown in the Figure 1 and the water supply pipes size and material distribution are shown in Table 1.

Table 1
Size and material distribution of pipes in Mbuya zone

Pipe No.	Pipe Material	Pipe diameter (mm)
2	Plastic-PVC	100
3	Plastic-PE	50
4	Plastic-PE	40
5	Steel	100
6	Plastic-PVC	100
7	Steel	100
8	Steel	100
9	Steel	50
10	Plastic-PVC	80
11	Plastic-PVC	80
12	Plastic-PVC	100
13	Plastic-PVC	50
14	Steel	100

Problem formulation

The analysis is a multiple time-step where scheduling of rehabilitation works is considered over a period of 25 years, in five-year steps. Each stage represents a five-year time segment in the planning horizon of 25 years. At each stage the decision variables represent different types of feasible rehabilitation strategies that are applicable to each pipe segment.

In this study, three rehabilitation options are considered; replacement, cleaning and do nothing. Repair costs of the pipes over analysis period are considered and determined by when it is replaced.

Costs of system

Repair costs (C1) =

$$\frac{BR(d_i,t)*BC(d_i)*BCF*l_i*5}{(1+r)^{5t}}$$

(1)

Where:
$BR(d_i,t)$ = failure rate for diameter d_i at time step t in expected bursts/km/year for pipe i as given in equation 12 and assumed average in a time step;
BC(d_i) = burst cost for Kampala Water;
l_i is the length of the pipe (km);
t = time step (0,1,2...5);
r is the discount rate;
BCF = Burst cost factor to cater for indirect costs i.e. traffic disruption and damage to third parties.

Replacement costs

The Present Value of the replacement cost of a pipe with diameter d_i in a time period t is given by:

Replacement (C2) = $\left(\frac{R(d_i)*l_i}{(1+r)^{5t}}\right)$

(2)

Where:
$R(d_i)$ = cost/m length of replacing the pipe with diameter d_i and is given by $1.1di^{1.5}$ (Vairavamoorthy and Ali, 2000; Savic and Walters, 1997). The unit cost function is adjusted to $R(d_i) = d_i^{0.6}$ to closely depict costs of Kampala Water. Table 2 gives the corresponding unit costs for the available diameters.

Cleaning costs (C3)

$$(C3) = \frac{0.06 * d_i^{0.6} * l_i}{(1+r)^{5t}}$$

(3)

Where $0.06^* di^{0.6}$ cost of cleaning pipes ($/m length); the unit cost for the cleaning option is a percentage of the replacement cost in equation (2). Table 3 gives the unit costs for the cleaning option for the available diameters.
The multiple time step problem is given as below:

Minimise (**whole life rehabilitation cost**) =

$$\min \sum_{t=1}^{5} system(\cos t_t)$$

(4)

Where:

$$\text{system}(\text{cost}_t) = \sum_{y=0}^{N} Cost_y(d_i)$$

(5)

Where:

$$Cost_y(d_i) = C1 + C2 + C3$$

(6)

N is the number of pipes in the network.

The constraints are:

- Conservation of mass in the distribution network

$$\sum_{j\epsilon j_i} Q_{ij} + C_i = 0 \quad \text{For all pressure nodes I}$$

(7)

Where Q_{ij} is the flow in the element connecting i and j; C_i is the consumption at node i and j_i is the set of all pipes connected to node i:

- Conservation of energy

$$\sum_{ij\epsilon p_l} \Delta H_{ij} = 0 \quad \text{for all } pl$$

(8)

Where ΔH_{ij} is the head loss in the element ij; pl is the set of all links that form the loop; $\Delta H_{ij} = Hi \ Hj$

- Minimum nodal pressures at all nodes

The pressure head hi being supplied at each demand node should be equal to or greater than the minimum allowed pressure head H^l.

$$h_i > H^l \text{ for all nodes I}$$

(9)

Penalty cost
The penalty cost was computed based on the sum of the pressure violation in all the violating nodes. This ensures that chromosomes with more nodes violating pressure and with large levels of violation have high penalty costs and those with few violating nodes and low levels of violation have low penalty costs. Rehabilitation strategies with no pressure violation at all nodes for the entire analysis period will have zero penalty; high fitness and greater chances of surviving to the next generation.
The penalty function used is as below:

$$\text{Penalty Cost} = \sum_{i=1}^{N} \gamma \left| H_{\min} - H_{actual} \right|$$

(10)

Where:
γ = penalty coefficient
H_{min} = Minimum allowable pressure
H_{actual} = Actual nodal pressure
N = Number of pressure violating nodes

A penalty coefficient of 1000 was used as this ensures that infeasible solutions are eliminated gradually from the population. A minimum allowable pressure value of 30m was considered.

Pipe condition prediction models

Pipe failure rate

Pipe break rate is one of the ways to account for pipe structural integrity. In order to estimate future repair costs for the different pipes in the network, it is necessary to predict pipe failure rates basing on available data (Dandy and Engelhardt, 2001).
From the equation for repair costs, it is necessary to predict pipe failure rates in five yearly intervals. It was not possible to model deterioration curves for this case study due to a lack of required data.
Therefore the pipe condition prediction model assumed in the research work is based on research work done in modelling the physical processes of pipe deterioration and failure.
The preferred model depicts an exponential increase in water main breakage rates over time as outlined below (Constantine and Darroch 1995; Marvin 1996).

Pipe Diameter (mm)	Unit cost ($/m)
100	15.8
80	13.8
50	10.5
40	9.1

Table 2
Unit costs for pipe replacement

$$y = ax^b$$

(11)

Where:
y = failure rate (breaks/km/year);
x = age of the pipe in years;
a and b are empirical coefficients

Pipe Diameter (mm)	Unit cost ($/m)
100	0.95
80	0.83
50	0.63
40	0.55

Table 3
Unit costs for cleaning option

The pipe deterioration model assumed in the model takes the following form and it is not representative of the case study situation.

$$y = 0.002 \exp(-0.01 d_i) age_i^2$$

(12)

Where
y = failure rate (breaks/km/year)
d_i = diameter of pipe i
age_i = age of pipe i (years)

The deterioration model depends on pipe material and environmental factors but in this optimisation model, it is assumed both pipe materials do obey the hypothetical function in equation 11.

Hydraulic carrying capacity

In modern cement-lined and plastic pipes, the pipe roughness changes slowly over the life of the pipe (with the exception of waters with significant scaling potential of poor removal of aluminium hydroxide flocs) (Walski et al, 1998). Knowledge of pipe roughness (C-factor) of in-place water mains is critical for network hydraulic performance and pipe sizing calculations.
(Walski et.al, 1998) proposed a conductivity coefficient deterioration model for an existing pipe as shown below:

$$C - \text{Factor}(t) = 18 - 37.2 \log \frac{e + a_i(t + g_i)}{D_i}$$

(13)

Where:
e = initial roughness in pipe i at the time of installation when it was new (m)
t = time elapsed from present time to future periods (years)
a_i = roughness growth rate in pipe i (m/yr)
g_i = age of pipe i at the present time (time of analysis) (years)
D_i = diameter of pipe i (m)

In the optimisation routine, the hydraulic carrying capacity of the pipes is assumed to obey the above model over the analysis period.

The initial roughness depends on the pipe material, but a typical value of 0.0006 ft (0.18mm) gives reasonable results for new pipes and is reasonably close to values reported by Lamont (1981) (Walski et al, 1998).

Methods to predict the roughness growth rate must take into account water quality. Colebrook and White (1973) reported values of roughness growth rate ranging from 0.000018ft/yr (0.066mm/yr) to 0.00017ft/yr (0.63mm/yr). In this model a is assumed to be 0.2mm/yr.

Genetic algorithms

Search technique has proven to find better solutions when applied to pipe network problems (Savic and Walters 1997) than other optimization techniques. The main advantage is the use of population of solutions that simultaneously search various parts of solution space, the long computation time for the different simulations is the main disadvantage.

GA representation of solution

GAs represents a solution as a string of numbers or chromosomes. They utilize genetic operators of selection, crossover and mutation to shuffle these individuals into new population based on individuals' fitness. This is repeated until convergence is achieved.

For the whole life cost rehabilitation strategy, six bits denoting decision variables at each five-year time step covering a period of 25 years represent each pipe. With a network of 13 pipes, a solution of 72 bits is considered. Decision variables at a time step are randomly selected, with chances of pipe replacement limited. Table 4 gives the GA representation for the timing and decision variables.

Table 4
Coding of chromosomes

Time step code	Time step in years	Options code	Option
0	0	0	No Action
1	5	1	Cleaning
2	10	2	Replacement
3	15		
4	20		
5	25		

Genetic operators

The GA begins by randomly generating the chromosomes for each individual in the population. These individuals are assigned a fitness value based on the solution's total cost including the penalty component. Some individuals are then selected for mating using the tournament selection method. Here a given number of individuals are chosen randomly from the population and then compete; the individual with the highest fitness undergo mating. The tournament size used was five. From selection there are two operators that are used to generate the offspring's chromosomes i.e. crossover and mutation.

The crossover function chooses a point randomly between both parents and the offspring inherit the genes of their parents along this crossover point. The offspring is recombined according to the probability of crossover. A cross over probability of 0.8 was used in the model as this seemed to be optimum value from trial runs.

In the whole life cost optimisation model, uniform mutation method was used where by a new value for each variable is chosen uniformly on an interval centred on the parent value. A mutation coefficient of 0.1 was used in the model for all the test cases used. A discount rate of 6% and a population size of 100 were considered.

Results

A maximum number of generations is specified at the beginning of the programme and the programme returns the lowest cost value recorded after the generations are completed. Three maximum generation numbers of 500, 1000 and 2000 were considered to identify consequences of this parameter to the result. Generation is the number of iterations the programme is allowed to perform.

The optimal cost values depict a slight improvement with increase in maximum number of generations. The run time of the programme increases with increase in number of maximum generations.

Table 5 shows the network rehabilitation strategy with optimal options for each pipe over the analysis period. (Maximum Generation Number 2000).

Comments

The results from the analysis above demonstrate the ability of the model in searching for good solutions for a small network where cleaning and replacement are the rehabilitation options. Though the global optimum may not be guaranteed, the solution obtained can be relied on as a good local optimum solution. Penalty function ensures that the infeasible solutions are eliminated.

The higher the maximum generation number, the better the solutions but this has a negative effect on the run time of the programme. Run time increases with increase in maximum generation number. The model has been tested on a small network of only 13 pipes; its performance in handling big networks is not ascertained.

Basing on research carried out in drinking water supply facilities in Municipalities in Canada, the NGSMI indicates that a water main with break rate greater than 4 breaks/km/year

Table 5
Network rehabilitation strategy

	Time					
Pipe	0 years	5 years	10 years	15 years	20 years	25 years
14	Cleaning	Cleaning	Cleaning	Cleaning	Cleaning	Cleaning
2	Cleaning	Cleaning	Cleaning	No-Action	Cleaning	Cleaning
3	Replace	Cleaning	No-Action	Cleaning	No-Action	No-Action
4	No-Action	Replace	No-Action	Cleaning	Cleaning	No-Action
5	No-Action	Cleaning	Cleaning	Cleaning	Cleaning	No-Action
6	Cleaning	No-Action	Cleaning	Cleaning	Cleaning	Cleaning
7	Cleaning	Cleaning	No-Action	Cleaning	No-Action	Cleaning
8	No-Action	No-Action	Cleaning	Cleaning	Cleaning	No-Action
10	Cleaning	Cleaning	No-Action	Cleaning	Cleaning	No-Action
9	Cleaning	No-Action	Replace	Cleaning	Cleaning	Cleaning
11	Cleaning	No-Action	Cleaning	Cleaning	No-Action	Cleaning
12	Cleaning	Cleaning	Cleaning	Replace	Cleaning	Cleaning
13	Cleaning	Cleaning	Cleaning	Cleaning	Cleaning	Cleaning

	Time					
Pipe	0 years	5 years	10 years	15 years	20 years	25 years
14	600.37	528.3	462.7	401.9	347	297.5
2	522.1	459.4	402.3	349.5	301.7	258.7
3	4339	205.4	34.6	168.9	82.6	98.5
4	606.3	1927.3	6	93	82.6	46.3
5	670.4	948	830.6	723.1	624.7	442.1
6	403.9	242.4	312	271	234	201.5
7	239.8	211.4	134.8	161.3	111.2	119.6
8	525.9	534.5	667.3	581.5	503.4	354.4
10	212	190.9	131.8	150.8	131.9	98.4
9	554.7	414.9	1319.6	62.5	54.7	51.4
11	571	337.7	471	421.6	297.9	328.9
12	456.5	432.9	403.6	938.1	44.4	38.87
13	340.6	302.5	266.9	235.7	206.9	180.1

Table 6
Costs of network rehabilitation at a time step (US$)

should be replaced. Therefore from the analysis above, most pipes at the 25 year time step would call for replacement.

The selection of the rehabilitation option for a particular pipe at a time step does not take into consideration the option selected in the preceding time step. The optimisation routine can be extended to cover this limitation by including a screening tool at the time step to ascertain pipe condition and accordingly assign feasible rehabilitation options.

Limitations

Whole life costs comprise of activity-based accounting and life cycle assessment; the model addresses the activity-based accounting, no account is taken for the life cycle assessment that covers social and environmental costs.

Considering an analysis period of 25 years, the water demand is presumably increasing as population grows. The model assumes the demand is constant and consequently pipe replacement was done with same diameter and material.

The model considers two options i.e. replacement and cleaning. Lining options (cement lining, epoxy lining and slip lining) are not catered for in the model.

Recommendations

- As already stated before, the C-factor is an indicator of the internal pipe roughness of, and critical for, network hydraulic calculations. The roughness growth rate used in the prediction of C-factors depends on the quality of the water, pipe material and the operation and maintenance practice. More research is needed for determination of roughness growth rate given different pipe type material and water quality parameters.
- From the study, it is apparent that pipe condition prediction models are vital in determining future rehabilitation costs and the timing of the replacement option. The models are practically supposed to vary depending on pipe physical factors, the environment and the operating conditions of the water distribution systems. It is therefore clear that such comprehensive models need to be developed and incorporated in optimisation tools to clearly account for the deterioration processes in terms of structural capacity and hydraulic capacity of water distribution systems.
- Including expected increases in the system demands during the analysis period and also considering diameters of the pipes for replacement as a decision variable can extend the model. With demand increase, issues of stable supply of water may arise so the rehabilitation strategy could further be extended to include reliability criterion thereby creating a multi-objective framework.
- As annual funds available to the water authorities for rehabilitation works of water assets are in most cases limited, there is need to improve the model by including budget constraints. The budget limitations could be useful if incorporated at each the time step over the analysis period.
- In the model, selection of a feasible option for a pipe at a time step is randomly done; this can be improved by pipe screening at each time step to ascertain pipe condition before assigning feasible rehabilitation options. The issue of getting pipes with break rates above recommended values will then not arise. ●

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Strategic infrastructure asset management: concepts, 'schools' and industry needs

Helena Alegre in this paper aims at launching the discussion about the International Water Association's (IWA's) future role and priorities with regards to strategic asset management of water and wastewater infrastructures. Examples of definitions of asset management, demonstrating the existing diversity and the bias in some of the existing approaches are shown; a subjective selection of the main 'schools' in infrastructure asset management is presented; the relevant standards and specifications are referred and industry needs identified, based on the outcome of previous asset management meetings and working groups.

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Introduction

Water and wastewater systems are critical infrastructures for any modern society. Many water distribution and wastewater drainage networks in Europe, especially in Central and Northern Europe, were built after the Great Wars and are reaching the end of their service life. The pipes show clear signs of deterioration, with a tendency to increased break rates, water losses and complaints on water quality and service efficiency. The condition of the assets is also problematic in other countries with more recent infrastructures, but where the quality of materials and the quality of construction is less good. In Portugal, for instance, the strategic priority was, for some decades, to increase the level of coverage, privileging quantity to quality. Water and wastewater utilities must manage their assets strategically, in order to bring them to adequate condition and serviceability levels. According to the Portuguese national survey INSAAR, there are around 33,000 km of water mains and 11,300 km of sewers (stormwater sewers excluded) in inland Portugal. Only EPAL, which is the Greater Lisbon water utility and is responsible for 2172 km of water mains, invested, in 2005, €46 million in the rehabilitation of their infrastructures (EPAL, 2006). This gives an order of magnitude of the national needs. However, in average, Portuguese water utilities invest below needs.

In the USA, a study carried out by the American Water Works Association (AWWA, 2001) found that 'by 2030, the average utility in the sample will have to spend about three and a half times as much on pipe replacement due to wear-out as it spends today. Even so, the average utility will also spend three times as much on repairs in that year as it spends today, as the pipes get older and more prone to breakage'.

In Canada, the National Research Council Canada estimates that the amount spent in maintenance and rehabilitation of municipal infrastructures is around one half of what it should be (Vanier, 2001).

In Australia and New Zealand there is already a great awareness and rather interesting solutions in terms of strategic asset management.

Given the significant investments involved, the decisions on how much, where, when and how to rehabilitate the networks must be well grounded, based on technical, functional and social-economic criteria. Such decisions are made difficult by the fact that these are buried infrastructures, not easily inspected, and thus implying indirect diagnostic and decision support methods.

The previously mentioned situation of investment needs for rehabilitation of water supply and wastewater networks require that know-how and operational tools are made available for decision support in this field. A change in culture is fundamental. Effective policies and regulation, awareness and training of the decision makers, innovative approaches, and scientifically and technically robust information and decision-support tools are required to pave the way towards a sustainable and high level of service to customers, ensuring the infrastructural, operational, financial, economic and environmental sustainability of water and wastewater utilities. 'Long term perspective', 'whole of life costs', 'risk management' are other key words in the context of modern water infrastructure management, nowadays commonly designated as 'strategic asset management' (SAM).

The International Water Association (IWA) has a role to play in these circumstances, creating awareness, disseminating the existing know-how, networking, contributing to the standardisation of concepts, and elaborating guidance documents for the utilities. LESAM 2007 was the second IWA Leading Edge Conference on Strategic Asset Management. The organisation of the LESAM conferences is in itself the recognition of the relevance SAM has gained in the international arena. IWA also publishes the reference newsletter Water Asset Management International (WAMI). A third key initiative of IWA is the establishment of the Strategic Asset Management Specialist Group (SAM SG), which met for the first time during LESAM 2007. The concrete role and activities of this group are still to be well defined.

This paper aims at launching the discussion about IWA future role and priorities with regard to strategic asset management of urban water infrastructures. It presents examples of definitions of asset management, demonstrating the existing diversity and the bias in some of the existing approaches; identifies the main existing 'schools' of thought in infrastructure asset management; and points out the need for further development, suggesting some of the most pressing issues.

Key concepts

Multiplicity of views

Although water supply and wastewater utilities have been managing their assets for a long time now, the term 'strategic asset management' was hardly used by the industry at all, beginning only a few years ago.

Asset management is a term established in the financial industry, where the trade-off between risk and return is of relevance. Approaches, techniques and tools developed for financial asset management can be – and have been – adapted to infrastructure asset management. However, this adaptation has been performed in many different ways by different people. The result is that the term infrastructure asset management encompasses rather different meanings to different individuals. Some keep the original financial connotation. Some place the emphasis on the business and management side, adding the organisational aspects to the financial asset management (i.e., how to implement a SAM approach in the organisation). Others see information management as the core issue. Engineers and researchers tend to consider that infrastructure asset management is centred on condition diagnosis, failure forecast and optimal rehabilitation planning.

This evolution is natural, and it is inevitable that professionals of a given area of knowledge tend to have biased views on a multidisciplinary subject. However, there is clearly a need for a common language on water and wastewater infrastructure asset management. This work has already started, but there is still a long way to go. The following sections focus on the basic concepts related to SAM.

Concept of 'infrastructure'

Water supply and wastewater utilities are organizations where physical assets are a key and critical factor in achieving its business objectives and in achieving effective service delivery. These physical assets comprise land assets (including rivers, urban creeks and urban, populated watersheds) and constructed infrastructures. All these elements are an integral part of physical systems which must be managed in relation to water and wastewater performance. However, the main focus of this paper is on the public infrastructure assets, which represent a very important part of the total water and wastewater utility assets.

Physical infrastructure assets are essential to provide a specific service, which may change over time, according to service needs and technology available.

The Publicly Available Specification (PAS) 55 (IAM/BSI, 2004) defines 'infrastructure assets' as a 'system of core assets, facilities and/or equipment'. Burns et al. (1999) provide a more detailed and comprehensive definition: 'Infrastructure assets … are defined functionally as assets that are not replaced as a whole but rather are renewed piecemeal by the replacement of individual components whilst maintaining the function of the system as a whole. Infrastructure assets have indefinite lives. Economic lives, however, can be assigned to individual components of an infrastructure system.'.

The most important notions to retain are that infrastructures are 'systems', not a set of independent assets, that have indefinite lives and that their target performance changes over time, being directed by the evolution of service needs and technology available. One of the consequences is that rehabilitation of an infrastructure shall be seen from a functional point of view. The aim of rehabilitation shall not be to recover the initial characteristics, but shall rather be to provide the necessary characteristics so that the infrastructure performs according to the actual needs and expectations.

Concept of 'asset management'

There are hundreds of definitions of asset management. It was previously referred that many of the existing views are biased towards a preferred point of view. Many others are alternative ways of expressing the same idea. Three broad scope and complementary ones are chosen in this section.

Brown & Humphrey (2005) propose a rather unusual but interesting definition: 'Asset management is the art of balancing performance, cost and risk. Achieving this balance requires support from three pillars of competence: management, engineering and information'. The word 'art' aims at pointing out that asset management cannot be seen as an exact science. It requires a lot of common sense and imagination. The other important message conveyed is that there is a conflict of interests in the whole AM approach: maximise the performance of the infrastructure and minimise risks associated on the one hand, and minimise costs on the other hand. The aim of AM is to achieve a sustainable balance between these vectors. Finally, the authors highlight the importance of the engineering, particularly important for the water supply and wastewater infrastructures, of the information management and of the various aspects of the organisation management: financial, economic, communicational, institutional, etc. This requires an effective multidisciplinary collaboration.

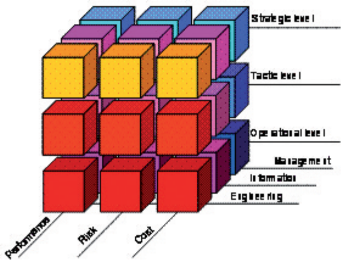
IIMM (2006) state that 'Asset management (AM) is the combination of management, economic, engineering and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner'. The same authors define 'Advanced asset management (AAM) as asset management which employs predictive modelling, risk management and optimised decision-making techniques to establish asset lifecycle treatment options and related long term cash flow predictions'. They also bring the attention to the need for adopting a multi-layer planning structure in the total asset management process, which includes *strategic planning, tactical planning* and *operational planning*.

PAS 55 (IAM/BSI, 2004) defines asset management as 'systematic and coordinated activities and practices through which an organization optimally manages its assets, and their associated performance, risks and expenditures over their lifecycle for the purpose of achieving its organizational strategic plan'. Additionally, PAS 55 defines 'organizational strategic plan' as 'the overall long-term action plan for the organization that is derived from and embodies its vision, mission, values, business policies, objectives and the management of its risks'.

This definition is one of the best founded in the literature. However, it may give the idea that the establishment of the strategic objectives and of the organizational strategic plan are external and independent from AM. This shall not be the case and in fact does not correspond to the spirit of the whole document. The term 'strategic asset management', adopted by IWA, aims at bringing the attention for the need of incorporating the strategic vision and planning in the AM approach.

Given the above, *strategic asset management* is a multidimensional

Figure 1
Dimensions of SAM (Alegre, 2007)



approach (Figure 1) that may be defined as the *corporate strategy* and the corresponding planning and systematic and coordinated *activities* and *practices* through which an organization optimally manages its assets, and their associated *performance, risks* and *expenditures* over their *lifecycle*. Performance should be seen in the long run and from a broad perspective, including all the relevant environmental, social and economic aspects for the various stakeholders, and particularly for the customers.

Potential levels of intervention of the IWA SAM SG

Strategic infrastructure asset management may be seen at two main levels: the administration level and the utility level. The IWA SAM SG has a potential leverage role in both cases. At the administration level, it should ideally contribute to:

- creating awareness to the politicians and to the society for the need of SAM;
- clarifying concepts and principles for the implementation of AM, by the elaboration of reference publications and manuals of best practice, and by the active participation of standardisation technical committees that may be created;
- assisting in the establishment of legal and institutional mechanisms that promote SAM;
- assuring that regulators do not confine their aim to higher service ability in the short and medium run;
- promoting international R&D projects.

At the utility level, the IWA SAM SG should ideally contribute to:

- implementing best practices, through the production of recommendations directed to utilities of different sizes and degree of development;
- networking utilities;
- changing the current predominant culture;
- improving the information structures and current information management practices;
- improving the organisational structure;
- adopting effective engineering decision support tools and solutions to the utilities;
- improving multidisciplinary and multi-departmental collaboration and communication between stakeholders.

WAMI newsletter and the Leading-Edge Conferences on SAM fulfil some of these objectives. It is up to the SAM Specialist Group to prioritise new initiatives. The future work of this Group has to be framed by the existing 'schools' of infrastructure asset management, by the on-going initiatives regarding standardisation and specification of concepts, principles and requirements and by the actual industry needs. These topics are covered in the following sections.

Main AM 'schools'

Introduction to AM schools

This section identifies some of the main recommended approaches to infrastructure asset management, generically referred to as 'schools'. It is a subjective selection, far from exhaustive. LESAM's papers and discussions may contribute to enhance this selection.

The leading role of Australia and New Zealand

Given its origin in the financial sector, where the economic approach is prevalent, accountants and economists were responsible for the first significant developments of infrastructure asset management. Back in 1986 and 1987, the South Australia Public Accountants Committee published a series of eight reports alerting all Australian governments to the need to seriously consider the management of their infrastructure if deterioration of valuable public services were to be avoided. Following these reports, Penny Burns, Professor at the University of Adelaide (Australia) played an essential role in bringing the attention to the importance of the subject and formalising some key concepts and principles (e.g., Burns, 1990, Burns et al., 1999). Nowadays, the leading role of Australia proceeds with the initiatives of the water utilities and of organisations such as the Institute of Public Works Engineering Australia (IPWEA, www.ipea.org.au), the National Asset Management Steering (NAMS) Group (www.nams.au.com), The Australian National Audit Office (ANAO, www.anao.gov.au), the Asset Management Quarterly International (AMQI, www.amqi.com), the ACORN Inc. (www.acorninc.org) and the Water Services Association Australia (WSAA, www.wsaa.asn.au).

The Australian and New Zealand AM 'school' is synthesised in the International Infrastructure Management Manual (IIMM), which is dedicated to different types of public infrastructures and promotes the total asset management process. This publication was jointly elaborated by the IPWEA and by the NAMS Group and has greatly evolved over time. The currently available third edition (IIMM, 2006) counted on contributions from other countries, such as the United States, South Africa and the United Kingdom, and is a true international reference. The IIMM states the difference between 'core AM' and 'advanced AM'. It aims at encouraging utilities to start with the basic features of an AM approach, which 'relies primarily on the use of an asset register, maintenance management systems, job/resource management, inventory control, condition assessment, simple risk assessment and defined levels of service in order to establish alternative treatment options and long-term cashflow predictions'. Advanced AM is «asset management that employs predictive modelling, risk management and optimised decision-making techniques to establish asset lifecycle treatment options and related long term cashflow predictions' (IIMM, 2006).

With regard to water supply and wastewater AM, Australia and New Zealand apparently present a bottom up approach, from the practice (utility associations and utilities) to the theory (academics and researchers). There are rather relevant experiences (e.g., Melbourne Water, Hunter Water, Westernport Water, Hobart Water). Interestingly, the formal economic developments do not have a clear transposition to the AM teams of the Australian Water utilities. Kelly (2005), from Seattle Public Utilities (USA), in a report of the results of a visit to Australia and New Zealand, refers that 'few of the utilities [visited] appeared to have economists. If they did, they seemed to be involved with pricing, net present value (NPV) models, and analysis. This fact may reflect the very significant difference between our countries in that most of the service and target setting is established by regulators in Australia, whereas here [in the US], in large part, we are figuring this out for ourselves. Furthermore, few utilities appeared to attempt to put dollars on intangibles'.

The 'six what' from the National Research Council Canada and the National guide to sustainable municipal infrastructure

Following the clear identification of the need for higher expenditures in maintenance and rehabilitation of municipal infrastructures in Canada, the National Research Council (NRC) Canada has had multiple initiatives directed to creating awareness and establishment guidelines for the implementation of AM approaches adequate to municipal infrastructures. According to the NRC, 'these typically include, but are not restricted to, the following classes of assets: buried utilities, roads, transit systems, bridges, water/sewage treatment plants and parks. Some jurisdictions are responsible for a variety of buildings (i.e., police stations, fire halls, indoor swimming pools, arenas and community centres) but their responsibility could also extend to other types of buildings such as social housing, schools and vehicle maintenance depots.' (Vanier e Rahman, 2004). The approach recommended by NRC may be synthesised in the structures reply to the following 'six what':

- What do you own?
- What is it worth?
- What is the deferred maintenance?
- What is the condition?
- What is the remaining service life?
- What do you fix first?

The work developed is applicable to any type or combination of municipal infrastructures. The activities related specifically to urban water infrastructures or to buried infrastructures is limited. The main focus with this regard is on the rehabilitation of metallic pipes.

The AM approach recommended by the NRC was incorporated into the InfraGuide: National guide to sustainable municipal infrastructure. This was a four-year project starting in 2001, financed in the scope of the Infrastructure Canada Program (ICP) and managed by the Federation of Canadian Municipalities (FCM) in partnership with the NRC. The guide contains a good number of independent documents presenting the best practices applicable to the management of various types of municipal infrastructures. The main areas of the guide are (http://sustainablecommunities.fcm.ca/Infraguide, ref, July 2007):

- Governance and Integrated Sustainable Development ('decision making and investment planning', 'environmental protocols' and 'integrated infrastructure');
- Water ('potable water' and 'storm and wastewater');
- Transportation ('roads and side walks' and 'transit').

The policy adopted of keeping the documents produced in the public domain, freely available in electronic version from the web, has greatly contributed to the dissemination of the knowledge created.

The European CARE-W and CARE-S systems

The twin systems CARE-W (Computer-Aided Rehabilitation of Water Networks) and CARE-S (Computer-Aided Rehabilitation of Sewer Networks) were developed under the 5th Framework Program of the European Union and aim at assisting water utilities in setting up strategic and tactical rehabilitation plans for water supply and wastewater networks (Sægrov, 2005, Sægrov, 2006). The projects ended respectively in 2004 and 2005, and since then a number of applications took place in various countries. More than a tool-kit, the CARE systems are a framework that comprises an integrated approach that promotes a global and integrated view of rehabilitation. Conversely, the tool-kit includes software applications that assist in the main phases of decision making process: characterisation, analysis and diagnosis, long term (strategic) planning and short term (operational) planning. The focus of the CARE systems is on buried assets. The emphasis is put on the engineering aspects.

Figure 2 shows the modules of CARE-W. CARE-S has a similar structure and architecture, although containing different modules, adequate to the wastewater systems.

The CARE approach, which is

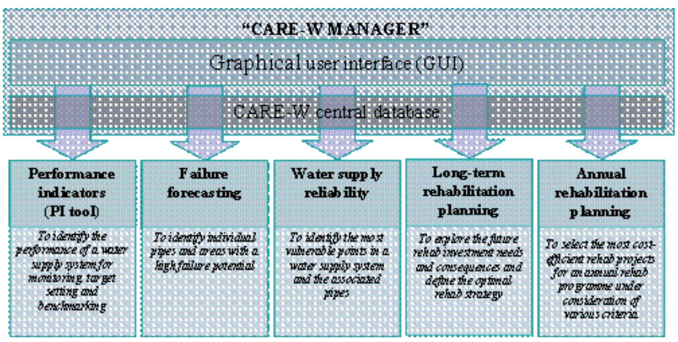


Figure 2
Modules of CARE-W prototype

contributing to a change of culture regarding network rehabilitation, is dealt with in other papers of this conference (Le Gauffre et al., 2007, Roh et al., 2007, Sægrov et al., 2007, Ugarelli et al., 2007, Werey et al., 2007).

The Common framework for capital maintenance in the UK

The Common framework for capital maintenance (United Kingdom) is a project undertaken with the support and collaboration of the Office of Water Services (OfWat), the Drinking Water Inspectorate (DWI), the Environment Agency (EA), the Water Industry Commissioner for Scotland and the Department for Environment, Food and Rural Affairs (DEFRA) together with the UK water industry (UKWIR, 2002). The development of the Common Framework was motivated by the Ofwat requirements for economic levels of capital maintenance to be demonstrated, as outlined in the Letter to Managing Directors MD161, issued in April 2000. It is based on the analysis of risk and encompasses an economic approach which allows the trade-off between capital and operational cost options to be considered. According to Lumbers et al., (2003), the following key concepts form the basis of the framework:

- capital maintenance should normally be justified on the basis of current and forecast probability and consequence of asset failure with or without investment;
- 'consequences' are expressed as direct impact on service and company costs;
- 'service' is defined to customers and the environment (including all relevant third parties and regulatory requirements);
- service is assessed using suitable indicators, building on the approach applied by Ofwat at the 1999 Periodic Review;
- there is a need to demonstrate a least cost approach to Opex versus Capex and proactive versus reactive maintenance;
- an integrated system approach is required for some systems to assess the direct and indirect impacts on customers and the environment.

Nowadays, the effect of the Common framework is felt not only in the UK, but also in many other countries, particularly in Europe, where the importance of its principles are being recognised and in some way implemented.

Other relevant European initiatives

Many other relevant European initiatives could be presented. Examples are:

- The UK has a leading role in other aspects of the urban water infrastructures AM, such as in the formalisation of whole-life cost optimization approaches and in the scope of water losses control.
- In The Netherlands, AM policies are directed by service targets, much more than by economic reasons. VEWIN, the Association of Dutch Water Companies and the Dutch research laboratory KIWA are two reference organisations with this regard.
- Germany adopts a pragmatic approach to AM materialised in the form of DVGW standards for asset condition assessment and rehabilitation.
- In Portugal, there are several on-going initiatives in the scope of R&D projects, utility applications and regulatory policy related to urban water system diagnosis, rehabilitation planning and investment prioritization. Key organizations are the National Civil Engineering Laboratory (LNEC) and IRAR, the water regulator.
- In many European countries AM is more developed in sectors such as railways, telecommunications, energy, highways, and airport infrastructures.

The US tool SIMPLE – Strategic infrastructure management planned learning environment

The American water works association Research Foundation (AwwaRF) and Water and the Water Environment Research Foundation (WERF) joined efforts and produced a tool for utilities called SIMPLE, which stands for 'Strategic infrastructure management planned learning environment'.

SIMPLE is a web-based tool that is designed to (i) provide a comprehensive understanding of asset management at strategic and operational levels; (ii) promote information exchange among asset management practitioners; and (iii) help implement asset management programmes at wastewater utilities. The SIMPLE knowledge base is developed around seven primary elements of life-cycle based asset management and entails user-friendly set of on-line practice guidelines, templates and decision support tools. It aims at assisting wastewater plants in learning about life-cycle asset management plans. By gathering asset management practices and processes from around the world, SIMPLE offers users an in-depth understanding of asset management for the wastewater collection and treatment facilities; SIMPLE is currently being enhanced through a new research project of AwwaRF and WERF to include drinking water as well (www.awwarf.org/research/TopicsAndProjects/projectSnapshot.aspx?pn=4013).

The case of Seattle Public Utilities and the USEPA advanced AM workshops

In the US, water infrastructure AM is rapidly developing. The US Environmental Protection Agency (USEPA) plays a key role with this regard (Albee, 2005a, Albee, 2005b). Among the multitude of initiatives, the series of US EPA advanced asset management workshops is particularly important. The recommended approach is greatly inspired in the Australian and New Zealand 'school'. However, it seems that there is still a long way to go in terms of practical applications. There are some good exceptions, such as Seattle Public Utilities, which started to implement a comprehensive AM approach in the early 2000s, also in-line with the Australian and New Zealand 'school' (Kelly, 2005).

The work developed in the US specifically for buried asset management is still limited. The application of the European CARE-W and CARE-S systems in Las Vegas (Vanrenterghem-Raven et al., 2007) demonstrates the feasibility and importance of adopting a coherent approach and using the right engineering tools to support the rehabilitation of buried assets.

The role of consultants and IT providers

Water utilities that decide to implement AM systems may face difficulties if they decide to carry out the job alone. There is a significant added value if they may count on the expertise and experience of AM consultants. However, utilities must understand AM is a corporate approach and not a plug and play system that can be purchased ready to use.

The same applies to providers of equipment to support condition assessment to information technologies (IT) providers. The availability of good commercial software applications in the scope of digital mapping (GIS – geographical information systems), of Enterprise Resource Planning (ERP) and of maintenance support systems, to mention just some of the most important types, greatly contributes to a better utility AM information structure and therefore to an improved AM, as a whole approach.

AM specifications and standards

Table 1 Regulation and standardisation

Action to develop	Proponent
'Developing common standards for AM focused on the internal environment (condition assessment standards that focus on condition or reliability, e.g., KPI (key performance indicators)'	EPA
'Adopt AM as a best practice standard and develop standard terminology and processes'	EPA
'Define asset management'	EPA

Need and availability of AM standards

The need for the establishment of clear terminology and specifications is a recurrent conclusion and recommendation from AM conferences and working groups (e.g., Albee, 2005b, Kirby, 2005, Vanier and Rahman, 2005, Wagner et al., 2003).

Several initiatives took place or are about to start as a reaction to this need. The British Institute for Asset Management took the lead and developed PAS 55, which defines requirements for an infrastructure AM system. The Technical Committee ISO TC 224 has just finalised the development of the ISO 24500 standards on 'Service activities relating to drinking water supply and sewerage' and raised the possibility of establishing a new work item on urban water infrastructures asset management. This was a topic of the agenda for its next meeting (Tokyo, November 2007). The ASTM International has launched a subcommittee on infrastructure AM.

The following sections briefly refer each of these initiatives, in order to provide a general overview that allows for a better coordinated action in the future. The IWA SAM should consider its role with regard to this matter, based on the analysis of the current situation.

Table 2 Topics to be developed with utilities

Action to develop	Proponent
'Get agreement on definition of AM between among the major professional water/engineering associations'	EPA
'LOS/AM Business model'	EPA
'Development of a central depository of high quality data available to researchers'	EPA
'Document case studies of improved customer service at reduced cost as a result of asset management'	GWRC

The PAS 55

The Publicly Available Specification PAS 55 (IAM/BSI, 2004) is a document jointly elaborated and published by the Institute of Asset Management (UK) and the British Standards Institution. According to its own contents, it 'is applicable to all sizes of business, from small to medium enterprises through to multinationals and to any organization that wishes to:

- implement, maintain and improve an asset management system;
- assure itself of its compliance with its stated asset management policy and strategy;
- demonstrate such compliance to others;
- seek certification/registration of its asset management system by an external organization;
- make a self-determination and self-declaration of compliance with PAS 55'.

PAS 55 is specifically intended to cover:

- the management of physical infrastructure assets (e.g., utility networks, power stations, railway systems, oil and gas installations, manufacturing and process plant, buildings, airports, etc.);
- asset management from an organizational perspective.

It is directed to organizations primarily dependent on the function of its physical assets in the delivery of services or products, and where the success of an organization is significantly influenced by the stewardship of the assets.

PAS 55 is based on the BS ISO format comparable with widely adopted standards such as ISO 14001 and OHSAS 18001, in order to facilitate its conversion into a BS or an ISO if there were a market requirement to do so.

It specifies 21 requirements for an asset management system for physical infrastructure assets, structured as follows: (i) General requirements of an asset management system; (ii) Asset management policy and strategy; (iii) Asset management information, risk assessment and planning; (iv) Implementation and operation; (v) Checking and corrective action; (vi) Management review and continual improvement.

Table 3 Manuals of best practice utilities

Action to develop	Proponent
'Publish a National version of the International AM manual'	EPA

PAS 55 has two parts. Its structure is prepared to accommodate a third part, for sector specific guidance. However, this aim has not been achieved yet.

The ASTM International Subcommittee F36.60 – 'Infrastructure asset management'

ASTM International established in July 2007 the Subcommittee F36.60 – 'Infrastructure asset management', under the Committee 'Technology and Underground Utilities'. This new subcommittee will develop standards dealing with the management of assets to support, primarily, underground water and wastewater utilities that will allow for larger communities to identify and utilize the level of specificity that is need for their asset management. It shall include, as appropriate, the above ground components of these systems that provide operational support to them.

It will, in principle, focus on water and wastewater utilities, due to the pressure by USEPA regarding pollution control of this aging infrastructure.

The activity will be primarily directed to larger communities but the aim is to keep information scaleable so as to have broad applicability.

The ISO 24500

The ISO 24500 is a set of three standards on service activities relating to drinking water supply systems and wastewater (ISO, 2007 a, b and c), currently in the form of FDIS (Final Draft International Standard). The final approval process is scheduled for fall of 2007. A brief description of their contents and the identification of their potential use as a support tool to manage assets is presented in another paper of this Conference (Cabrera et al., 2007).

These standards are the first ISO 'service' standards. So far ISO had published 'product' and 'process' standards. Although they are not AM standards, the principles established and all their contents fit well the principles of an AM approach. They are therefore a reference document to be taken into account in future guidance documents of specific standards on urban water infrastructure asset management. Conversely, the technical Committee that elaborated these standards (ISO/TC 224) is considering the interest and opportunity of developing of a standard for water and wastewater AM.

Complementary fields of standardisation

Some countries developed accounting standards more adequate to an AM approach than the traditional ones (e.g., GASB 34 in the US or AAS27 in Australia).

Risk management, fundamental for a proper AM, as also been object of standardisation (e.g., AS/NZS, 2004a, AS/NZS, 2004b, IRM et al., 2002, ISO/IEC, 1999, ISO/IEC, 2002, Kenning, 2001).

Data and software standards is another field essential for AM and where developments have been remarkable. AM being data seek and requiring the use of data stored in very different platforms, greatly depend on an effective data integration.

The role of the IWA SAM SG with regard to AM specifications and standards

It is the IWA SAM SG's duty to contribute to the development of standards and specifications for urban infrastructures AM. Main alternatives are:

- Serve as a facilitator between the various concurrent on-going initiatives in order to promote cooperation and prevent overlapping;
- Participate actively in existing and emerging standardisation committees;
- Launch its own agenda, developing a manual of best practice.

These alternatives are not mutually exclusive. The group has to analyse them and define a strategy.

Industry needs

IWA SAM SG may assist in setting up an international research and development strategy on urban water infrastructures asset management that corresponds to the actual industry needs. The greatest challenge in setting up a common agenda is not so much the identification of new research topics, but rather how to better apply the existing knowledge, tools and existing research results. Again, the action of the group should take into account the existing results from previous work.

There is already much more collaboration occurring between European, Australian and American research associations. Current examples of where this is occurring between organizations like WERF, GWRC, AwwaRF, and WSSA are on joint research being conducted on risk management, cost effectiveness, and case study development. However, there is plenty of room for greater collaboration and cooperation on this front. Tables 1 to 5 present a synthesis of topics identified as relevant in various international forums (Alegre, 2007), and aim at highlighting that many common interests exist, showing the potential of collaboration. This synthesis is based on documents published between 2003 and 2005. The views of the organisations quoted have evolved in the meantime, and some are about to publish new priority lists related to SAM. However, as this information is not publicly available yet, it is not incorporated in the analysis. References taken into account are:

- Assessment by the Global Water Research Coalition (GWRC) (Kirby, 2005);
- Research priorities for successful asset management: a workshop (WERF) (Wagner et al., 2003);
- Working session exploring opportunities to enhance collaboration by water and waste water utilities in advancing asset management (USEPA) (Albee, 2005b);
- Open forum on opportunities for research in asset management in Canada (MIIP) (Vanier and Rahman, 2005).

Table 4
Applied research topics

Action to develop	Proponent
'A compendium of approaches to asset management'	GWRC
'Construct a template for preparing infrastructure asset management plans'	WERF
'Prepare guidance for asset management strategic planning'	WERF
'Tools / techniques to incorporate sustainability into AM'	EPA
'Life cycle maintenance best practices for process, procedure, timing, risk'	EPA
'Identify O&M best practice in asset management'	GWRC
'Construct predictive lifecycle models for water and wastewater infrastructure that project lifecycle costs and risks'	WERF
'Development and acceptance of standardized and defined levels of service'	MIIP
'Develop predictive tools for performance prediction'	GWRC
'Risk management for strategic assets'	GWRC
'Develop common / Best Practice for risk management framework'	EPA
'Alignment of different risk management approaches'	GWRC
'Develop practical methodologies for calculating lifecycle costs for water and wastewater infrastructure assets'	WERF
'Establish methodologies for determining water and wastewater asset values, compiling asset inventories and capturing and compiling asset attribute information'	WERF
'Develop protocols for assessing the condition and performance of water and wastewater infrastructure assets and develop predictive models for correlating asset condition and performance'	WERF
'Research and development of standardized condition assessment protocols for municipal infrastructure'	MIIP
'Research on tools for cost effective physical conditions assessment including design standards'	EPA
'Develop predictive models for correlating asset condition and performance of aboveground assets'	GWRC
'Data requirements [and standards (common language)] to support deterioration modelling of sewers'	GWRC
'Deterioration modelling of sewers'	GWRC
'Data requirements and standards (common language) to support deterioration models for water mains'	GWRC
'Deterioration modelling of mains'	GWRC
'Identify operations and maintenance best practice by asset category, condition and performance requirements'	WERF
'Relationship between planned and unplanned O&M and effect on WLC'	GWRC
'Define best practices for the integration of water and wastewater databases'	WERF
'Identify best practice for water and wastewater databases'	GWRC
'Objective reviews of AM software'	MIIP
'Creation of a 'toolbox' or repository of standard software methods'	MIIP
'Economic benefit/cost analysis research identifying life cycle and social costs of infrastructure intervention'	MIIP
'Standard methods for comprehensive benefits analysis (economic and noneconomic)'	EPA
'Culture change'	EPA
'Develop techniques that secure improvement in efficiency and effectiveness within organizations'	GWRC

Concluding remarks

Strategic asset management of urban water infrastructures is essential for the sustainability of the water supply and wastewater services. IWA recognised that it has a role to play with this regard and established the LESAM Conferences, the newsletter 'Water Asset Management International' and, more recently, the SAM Specialist Group. The specific action of SAM is still to be defined. The strategy and the action plan of the Group have to take into account the existing knowledge and developments, as well as the water

Action to develop	Proponent
'Post graduate degrees in public infrastructure management'	MIIP
'Revise existing engineering and other related courses'	EPA
'Dedicated conferences and workshops in Canada and abroad focusing on infrastructure management'	MIIP
'[National] workshop on asset management'	MIIP

Table 5 Training and dissemination

industry needs. This paper provides a synthetic overview, inevitably subjective, aiming at launching the discussion. ●

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Assessing the benefits of rehabilitation programmes defined with the CARE-W decision support system

CARE-W_ARP is a multicriteria decision support software prototype for the construction of annual rehabilitation programmes of water networks. Two main components may be distinguished in ARP: a) a set of criteria was formulated for the purpose of assessing and comparing water mains; criteria related to the various consequences of pipe failures (leaks and bursts) are expressed by using risk concepts; b) a multicriteria ranking procedure was developed, based on the ELECTRE Tri outranking method. This procedure assigns each pipe to one out of six possible priority levels.

Within two PhD studies, CARE-W_ARP was used as a research tool. Full scale experiments and critical analyses were conducted with data on the asset stocks of Reggio Emilia (Italy) and Lyon (France). These studies proposed new developments and provided original results. A new criteria formulation was proposed to assess the efficiency of rehabilitation projects and a second set of criteria was defined for assessing and comparing rehabilitation programmes. A comparison between four scenarios tested in Lyon shows that a rehabilitation programme elaborated with the support of CARE-W_ARP provides higher benefits than other scenarios. An experiment with data from Reggio Emilia provided similar conclusions. In this paper, Pascal Le Gauffre, H. Haidar and David Poinard discuss the results from these studies.

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Introduction

CARE-W

The aim of the European Project CARE-W (2001-2004) was the development and testing of complementary models and tools for the design and the exploration of rehabilitation strategies and programmes for water supply networks (Sægrov, 2005). Three complementary approaches were adopted for supporting rehabilitation of water distribution systems. The first one is the development of guidelines for continuous observation of the performance of the network and the utility. It consists of the definition and the evaluation of a set of performance indicators (concerning pipe failures, water losses, customer complaints, etc.) that are calculated on network level, zone level, or even on pipe level (Alegre *et al.*, 2000; 2005). Secondly, the development and the calculation of long-term strategies of rehabilitation is an approach that refers to the estimated service life of pipe types and to the efficiency of rehabilitation programmes. Strategies are defined by the length of pipe types that will be replaced or renovated in the future. The long-term-strategy module of CARE-W is designed for the forecast of future rehabilitation needs, and the benefits that can be expected from selected strategies by calculating the pros and cons in terms of indicators with or without rehabilitation (Herz *et al.*, 2005). The third approach deals with prioritisation of rehabilitation needs: the CARE-W_ARP module is dedicated to the definition of Annual Rehabilitation Programmes (Le Gauffre and Torterotot, 2005).

CARE-W_ARP

Two main components may be distinguished in ARP:

- a multicriteria ranking procedure was developed, based on the ELECTRE Tri outranking method (Rogers *et al.* 2000); this procedure assigns each pipe to one out of six possible priority levels (Le Gauffre *et al.*, 2007)
- a set of criteria was formulated for the purpose of assessing and comparing water mains; each criterion is a measure of a particular impact or risk linked to the condition of a pipe. Information required for the calculation of the proposed decision criteria is derived from four main sources (Figure 1)

The four main data sources are:

- Performance indicators (PIs): for example, criteria WQD (Water Quality Deficiency) and WLI (Water Losses Index) may be calculated by the CARE-W_PI tool at a zone or district level;
- Hydraulic Reliability software: calculation of criterion HCI (Hydraulic Criticality Index) requires hydraulic modelling and simulations provided by three alternative software tools: CARE-W_Aquarel, CARE-W_Failnet or CARE-W_Relnet;
- Failure prediction tools: to supply predicted burst rates per pipe (CARE-W_Fail_PHM or CARE-W_Fail_Poisson);
- Utility Databases: to supply information on the pipe environment, surface type, population supplied, and so on. All these data have to be obtained from data sources managed by the water utility or other utilities (roads and traffic, urban planning, etc.).

Full scale experiments of CARE-W_ARP

Within two PhD studies, conducted in 2004-2006, CARE-W_ARP was used as a research tool. Full scale experiments and critical analyses were conducted by using data on the asset stocks of Reggio Emilia (Italy) (Haidar, 2006) and Lyon (France) (Poinard, 2006). These two research studies proposed new developments and provided original results: a new criteria formulation was proposed to assess the efficiency of rehabilitation projects and a second set of criteria was defined for assessing and comparing rehabilitation programmes (alternative selections of a subset of pipes within the asset stock); results of numerical experiments provided an assessment of the real efficiency of fictitious rehabilitation programmes, depending on the criteria used and on the data and tool used for predicting pipe failures. These results are presented in the next sections.

Back to the formulation of decision criteria

Risk-based criteria

Within CARE-W_ARP, criteria related to the various consequences of pipe failures (leaks and bursts) were expressed by using risk concepts and a formulation proposed by Varnes (1984) and Tira (1997): $R=PxIxVxE$ where R is a particular measure of risk, I refers to the intensity of a disruption, P refers to the probability or frequency of the disruption, V and E refer to the vulnerability and the value of the exposed environment. Table 1 presents the formulation of the proposed criteria.

PFR (PBR) is the predicted failure (burst) rate, calculated with CARE-W_FAIL (Eisenbeis, 2005) for each individual pipe (failures include bursts and leaks).

EDI is the expected duration of service interruption (hours), and has to be defined by water utilities by using available statistics. For instance asbestos-cement pipes may be associated to higher values of EDI (due to specific precautions on site). *P (pressure)* and *D (diameter)* are also considered as aggravating factors when a break occurs.

IFH and *LS* are indices that may be used for defining several urban contexts where values may be more or less exposed to some possible consequences

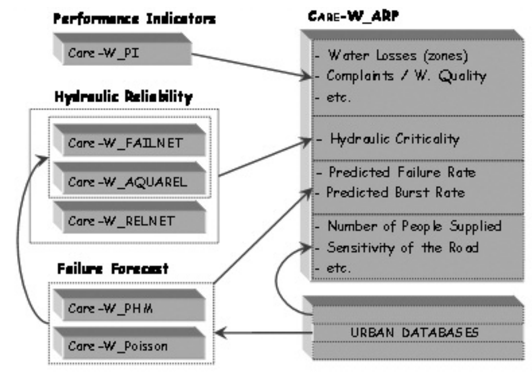

Figure 1
Data sources and flows for supplying CARE-W_ARP

of breaks: damages due to flooding, damages due to a landslide.

NPS (number of people supplied), SC (sensitive customers), SI (sensitive infrastructure) and SR (sensitivity of the road) refer to the exposed people or values. Table 2 provides an example derived from studies on the asset stock of Lyon.

Risk-based criteria, taking account of replacement costs

The original formulation, presented in the previous sub-section, refers to risks generated by the current condition of the assets. However two pipes that generate similar impacts or risks may correspond to very different rehabilitation costs. In Table 3 we present an alternative formulation for decision criteria: criterion *PWI (predicted water interruptions)* is used as an example; we denote PWI^* the alternative criterion and UCR_k the unit cost of replacement (k€/100m) for pipe k.

PWI^*_k expresses the efficiency of replacing pipe k (avoided annual impacts / k€ dedicated to replacement) regarding water interruptions. Similarly, $PCWI^*$, ARC^* … may be used to assess the efficiency of replacing pipe k regarding other consequences of pipe failures: disruptions of sensitive customers, repair costs, etc.

Results of some experiments performed by (Haidar, 2006) showed that this formulation is a more relevant option than the use of a complementary criterion '*Rehabilitation cost*'. Note that we only propose a formulation for the case of replacement: in this case we expect that no failures will occur in the near future. Dealing with other rehabilitation options would require an estimation of the pipe failure rate after the pipe renovation.

Table 1
Risk-based criteria related to the consequences of pipe failures

Risk components : Criteria	P	I	V	E
PWI: Predicted Water Interruptions	*PBR* (1/100m.year)	*EDI* (hours)	/	*NPS* (persons)
PCWI: Predicted Critical Water Interruptions	*PBR* (1/100m.year)	*EDI* (hours)	/	SC $\in$ [0.1] sensitivity
ARC: Annual Repair Costs	*PFR* (1/100m.year)	/	/	*UCRp* (€) repair cost
DFH: Damages due to flooding in housing areas	*PBR* (1/100m.year)	$P.D^2$	*IFH* $\in$ [0,1] flooding intensity	*VHF* $\in$ [0.1] exposed values
DSM: Damages due to soil movements	*PFR* (1/100m.year)	$P.D^2$	*LS* $\in$ [0,1] risk of landslide	/
DDI: Damages or Disruptions on other infrastructure	*PBR* (1/100m.year)	$P.D^2$	/	*SI* $\in$ [0.1] sensitive infra
DT : Disruption of the traffic	*PBR* (1/100m.year)	/	/	*SR* $\in$ [0.1] sensitive road

Criteria for comparing alternative rehabilitation programmes

In this sub-section we will focus on a new set of criteria that was proposed for the purpose of comparing alternative rehabilitation programmes. We denote:

- *AS*: the considered asset stock (a set of pipes that are candidates for rehabilitation);
- P_j: j^{th} alternative rehabilitation programme;
- $LR(P_j) = \sum_{k \in P_j} L_k \Big/ \sum_{k \in AS} L_k$

: length rehabilitated (%) (with L_k the length of pipe k);

- $CR(P_j) = \sum_{k \in P_j} L_k \times UCR_k \Big/ \sum_{k \in AS} L_k \times UCR_k$

: cost of a rehabilitation programme (%).

The proposed criteria express the *expected efficiency (EE)* of a rehabilitation programme: they refer to the *expected benefit (EB*, avoided impacts thanks to the implementation of the rehabilitation programme) and to the extent of the rehabilitation programme (*LR* or *CR*). Table 4 provides an example dealing with water interruptions.

For instance, $LR(P_j) = 2\%$ and $EB(P_j, PCWI) = 38\%$ gives $EE(P_j, PCWI) = 19$: rehabilitating 2% of the total length of the network is expected to avoid 38% of the annual impacts on sensitive customers (expected efficiency of this rehabilitation scenario: $EE = 38 / 2 = 19$).

The next subsection is dedicated to the use of these criteria.

Comparing alternative rehabilitation programmes … and defining rehabilitation goals

This subsection provides an example of a procedure for exploring contrasting rehabilitation programmes.

Comparing alternative programmes that can be generated with CARE-W_ARP is a way of studying the impact of several parameters that are used within the ELECTRE TRI procedure: criteria weights, profiles that are used as references for assigning each pipe to one category, etc. (Figures 2a, 2b).

Comparing alternative programmes according to several efficiency criteria is also a way of balancing various rehabilitation goals: reducing water losses, reducing disturbances to the urban environment, reducing annual repair costs, etc.

Using data from Reggio Emilia, Haidar (2006) ran the CARE-W_ARP module for generating and comparing fictitious alternative rehabilitation programmes. Each run of the ELECTRE Tri procedure uses a given set of parameter values (weights, reference profiles, etc.) and the output is a subset of pipes assigned to the highest priority group (denoted C33). Figure 2b provides an example: 67 pipes (out of 2729) are assigned to group C33. Let us consider this group of pipes as a possible rehabilitation programme.

Figure 3 displays some results of an experiment where three possible rehabilitation programmes were compared. Each programme is a subset of pipes representing about 1.4 % of the total length of the network.

Five criteria (g_i) were used within the ELECTRE Tri procedure: *PWI (water interruptions), PCWI (critical interruptions), DT (traffic disruptions), ARC (repair costs)* and *WLI (water losses index)*. The expected efficiencies $EE(P_j,g_i)$ were used as criteria for comparing alternative programmes P_j; for $g_i=WLI$ the expected efficiency is replaced by an index that is the mean value of *WLI* within the chosen pipes ($WLI\_m \in [0,1]$).

Let us compare three alternatives displayed in Figure 3.

Alternative *P2* appears as the best option if the main objective is to reduce the various consequences of pipe breaks (interruptions, disruptions and costs).

Alternative *P6* appears as a very good option if the main objective is to reduce water losses (*WLI_m* close to 0.9 means that all the rehabilitated pipes are situated in leaky districts). Unfortunately $EE(P_j,PWI)$ is strongly reduced (from 14.7 to 6.6) and this is also the case for $EE(P_j,PCWI)$.

Alternative *P5* may appear as a good compromise.

These three possible programmes were generated by 'playing' with parameters: for instance the weight associated to criterion *WLI* was increased from w = 0.1 for *P2* to w = 0.3 for *P5* and w = 0.4 for *P6*. Other weights and values of the two reference profiles were also modified from *P2* to *P5* and *P6*.

This is the way that we suggest for defining weights and other parameters within the ELECTRE Tri procedure. With this 'what-if?' approach the decision process is considered as an exploration of contrasting scenarios: a first step is the construction of contrasting options; a second step is the selection of an option/goal.

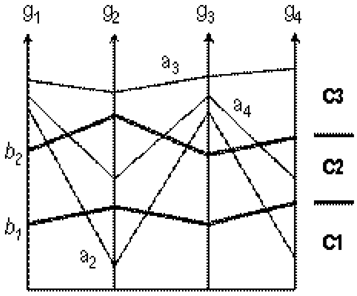

Figure 2a
Each pipe (a1, a2 …) is assessed according to criteria g1, g2… Two profiles denoted b1 and b2 are used as references. They define the limits between three priority levels (C3 > C2 > C1)

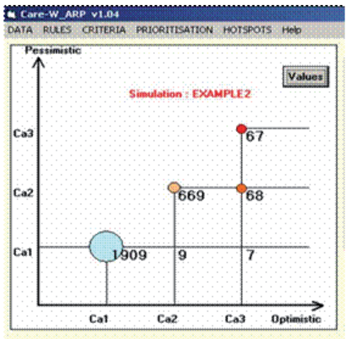

Figure 2b
By using two ranking procedures, ELECTRE Tri provides a way of defining six groups within the asset stock (2729 pipes in Reggio Emilia)

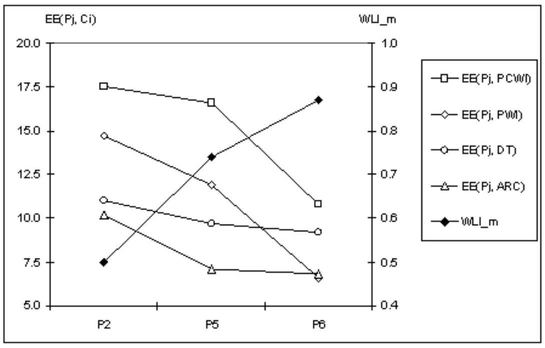

Figure 3
Three alternative rehabilitation programs (P2, P5 and P6: three subsets of pipes selected by using CARE-W_ARP with three different sets of parameter values) compared with five criteria

Benefits of rehabilitation programmes

The expected benefits *(EB)* and the expected efficiencies *(EE)* that have been presented in the previous section were proposed for the purpose of comparing possible future programmes; in this section we examine the real benefits and the real efficiencies that were calculated for fictitious programmes that could have been implemented some years ago in Lyon or in Reggio Emilia.

Poinard (2006) performed a numerical experiment for estimating the benefits of using the CARE-W_ARP prototype for the Lyon network. The available failure history was 1993-2004. The experiment aimed at comparing four scenarios:

- Scenario S1: a rehabilitation programme (3% of the total length of the network) was implemented at the end of year 2001; pipes were chosen according to the pipe age;
- Scenario S2: a rehabilitation programme (3%) was implemented at the end of year 2001; pipes were chosen by ranking pipes according to the individual failure rate;
- Scenario S3: a rehabilitation programme (3%) was implemented at the end of year 2001; pipes were chosen by using CARE-W_ARP;
- Scenario S0 serves as a reference: no rehabilitation done between 2001 and 2002.

These four scenarios were tested by identifying pipe failures that occurred in 2002-2004 and which could have been avoided with a given rehabilitation scenario. The reduction of the number of pipe failures was calculated for several subsets of pipes: the whole asset stock, pipes that supply sensitive customers, pipes that are located in areas prone to landslide, pipes below sensitive roads. Results are displayed in Table 5. 1138 pipe failures occurred during the three-year observation period (2002-2004). Scenario S1 (criterion: pipe age) provides very poor benefits (-64 failures) while scenario S2 (criterion: failure rate) allows to avoid 21% of the total number of failures (-238 failures). Scenario S3 (use of ARP) provides interesting results:

- 183 failures (only) could have been avoided on the whole network (instead of 238 with S2);
- on the other hand, 152 out of 768 critical failures (cases a, b or c) could have been avoided thanks to scenario S3 (instead of 110 with S2);
- benefit of scenario S3 is particularly high for the subset of pipes that are located in areas prone to landslide: 34% of the observed failures (52 out of 154) could have been avoided; (landslide is a major concern in Lyon; thus criterion DSM – Risk of damages due to soil movement, was a priority criterion in the application of the ELECTRE Tri procedure).

A similar experiment was conducted by Haidar (2006) with data from Reggio Emilia. Table 6 displays the 'real

Table 2
Values of SC (sensitivity of customers) chosen in Lyon by Poinard (2006)

Category	SC	Definition	% of the asset stock
1	1	Hospitals, customers using dialysis machine, …	4.0%
2	0.5	Nurseries, schools, universities …	9.1%
3	0	Other cases	86.9%

Table 3
Two alternative formulations of a criterion dealing with water interruptions

Alternative formulation	Formula	Unit
Formulation 1	$PWI_k = PBR_k \times EDI_k \times NPS_k$	Persons.hours/(100m.year)
Formulation 2	$PWI^*_k = \dfrac{PBR_k \times EDI_k \times NPS_k}{UCR_k}$	(Persons.hours/year) / k€ (avoided annual impacts / k€)

Alternative formulations	Scales: Pipes	Alternative rehabilitation programmes
1	$PWI_k = PBR_k \times EDI_k \times NPS_k$	$EB(P_j, PWI) = \dfrac{\sum_{k \in P_j} PWI_k \times L_k}{\sum_{k \in AS} PWI_k \times L_k}$ and: $EE(P_j, PWI) = \dfrac{EB(P_j, PWI)}{LR(P_j)}$
2	$PWI^*_k = \dfrac{PBR_k \times EDI_k \times NPS_k}{UCR_k}$	$EE^*(P_j, PWI) = \dfrac{EB(P_j, PWI)}{CR(P_j)}$

Table 4
Criteria formulated for assessing and comparing pipes or annual programmes (examples related to water interruptions induced by pipe breaks)

benefits' of two fictitious rehabilitation programmes. The observation period is 1999-2001. Real benefits were calculated as for the expected benefits (Table 4) but *PFR* (predicted failure rate) was replaced by the observed failure rate. CARE-W_ARP was performed by using criteria calculated with *PFR* provided by statistical tools supplied with failure data from 1994 to 1998.

Scenario S1 is a rehabilitation programme based on pipe failure rates. This scenario provides poor benefits regarding water interruptions. Scenario S2, where rehabilitated pipes were selected by using CARE-W_ARP, provides much higher benefits: 35% of the impacts on sensitive customers could have been avoided by replacing 2% of the total length of the network, 21% of the impacts on customers could have been avoided, etc.

Other experiments were conducted for the purpose of studying the impacts – on the efficiency of rehabilitation of programmes – of failure prediction tools, availability of failure data, availability of data used in statistical tools, etc. Results of these experiments are reported in (Haidar, 2006).

Conclusions

CARE-W is a set of tools that were developed for the purpose of supporting the construction of rehabilitation strategies and annual rehabilitation programmes. After the development of these prototypes one important issue was to assess the benefits of using such tools. Regarding CARE-W_ARP, full scale experiments – together with critical analyses – were conducted within two doctoral theses with data from Lyon and Reggio Emilia. Results were obtained concerning the benefits of using a multicriteria representation and a multicriteria ranking procedure.

In this paper we present a new formulation of criteria that was proposed for assessing the efficiency of rehabilitation projects and a second set of criteria that was defined for assessing and comparing rehabilitation programmes (alternative selections of a subset of pipes within the asset stock).

Results of numerical experiments provided an assessment of the efficiency of rehabilitation programmes depending on the criteria used for their definition.

A comparison between four scenarios in Lyon showed that a rehabilitation programme elaborated with the support of CARE-W_ARP provides higher benefits than other scenarios. An experiment with data from Reggio Emilia provided similar conclusions. ●

Subsets of pipes	Number of breaks observed during three years (2002-2004): No Rehab. Programme (S0)	Rehabilitation programme; 3% of the total length of the network selected according to: Pipe age (S1)	Pipe failure rate (S2)		CARE-W_ARP (S3)	
Whole asset stock (~ 3000 km)	1138	-64	- 238	(- 21%)	- 183	(- 16%)
a) pipes supplying sensitive customers	43	0	- 11	(- 26%)	- 12	(- 28%)
b) pipes in areas prone to landslide	154	-13	- 29	(- 19%)	- 52	(- 34%)
c) pipes below sensitive roads	627	-38	- 92	(- 14%)	- 114	(- 18%)
a) or b) or c)	768	-46	- 110	(- 14%)	- 152	(- 20%)

Table 5
Pipe failures avoided in 2002-2004, for three fictitious rehabilitation programmes, implemented at the end of 2001, and defined by using failure data from 1993 to 2001 in Lyon (Poinard, 2006)

Real benefits (similar to the expected benefits but calculated with failures observed in 1999-2001)	Rehabilitation programme; 2% of the total length of the network selected according to: Pipe failure rates (S1)	CARE-W_ARP (S2)
RB(*PWI* – Predicted water interruptions)	3.01	21.5
RB(*PCWI* – Predicted critical water interruptions)	2.47	35.4
RB(*ARC* – Annual repair costs)	8.40	9.7
RB(*DT* – Traffic Disruptions)	10.95	16.2

Table 6
Real efficiencies of two fictitious rehabilitation programmes implemented at the end of 1998 and defined by using failure data from 1994 to 1998 in Reggio Emilia (Haidar, 2006)

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Strategies for integrating alternative groundwater sources into the water supply system of the Algarve, Portugal

The future availability of drinking water in the Portuguese Algarve region is put at risk by the continuing rise in water demand, the decreasing amount of rainfall and the increasing potential for the occurrence of more-intense or longer-lasting drought periods. Moreover, tourism and agriculture, the two main economic activities in the region, rely heavily on the available water resources, and particularly during dry periods, pose a threat to the public water supply. Until recently, the multimunicipal public water supply system (MPWSS), created in 2000 and managed by the regional Water Utility Águas do Algarve, was entirely based on surface water provided by large reservoirs. During the extreme drought of 2005, serious consequences of this single-source strategy were felt, when several reservoirs reached their exploration limit, and could not satisfy the water demand.

During that period, the regional water utility realized that in order to guarantee public water supply in the long-term, a strategy based on an integrated water resources management (IWRM) scheme is needed. Therefore, alternative water sources need to be integrated into the MPWSS, the most important one of which is groundwater, the principal source of public supply in the Algarve before the existence of the MPWSS. Currently, a decision-aid model that will promote the IWRM in the region is being developed. In this paper In this paper, T.Y. Stigter, J.P. Monteiro, L.M. Nunes, J. Vieira, M.C. Cunha, L. Ribeiro and H. Lucas highlight one of the necessary tasks for that model, namely a screening selection of groundwater wells with sufficient quantity and quality to allow their integration into the water supply network. The quantitative criteria are based on aquifer properties and well yields. The results indicate that over 40 existing municipal wells, with a total yield of more than 1000 l/s, can be integrated into the MPWSS. An additional 25 wells (600 l/s) will be usable after appropriate disinfection and iron and manganese removal, or mixing with surface water.

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Introduction

The extreme seasonal and annual variations in rainfall in semi-arid regions such as the Algarve pose serious challenges to stable and sustainable water supply planning and management. Moreover, the intensity and frequency of occurrence of extreme droughts will most likely increase significantly in the future, according to the large-scale study of climate change in Portugal (Santos and Miranda, 2006). At the same time, the water demand in the region is continuously increasing, owing to the growth of population and tourism, the principal economical activity of the region. According to the 2001 population census, the registered population in the Algarve increased 15% between 1991 and 2001, by far the largest rate in the country and solely caused by migration. Tourism is responsible for an additional ten million visitors each year, mostly during the summer months. On the other hand, agriculture is the major water-consuming activity in the area. Total annual water consumption in the Algarve is currently estimated to be 260 million m³, of which 72% is for agriculture, 20% for public supply and 8% for golf courses (Monteiro and Costa, 2004).

The multimunicipal public water supply system (MPWSS), created in 2000 and managed by the regional Water Utility Águas do Algarve, up to 2005 was entirely based on surface water provided by large reservoirs. During the extreme drought of 2005 serious consequences of this single-source strategy were felt, when several reservoirs reached their exploration limit, and could not satisfy the water demand. Currently, another large dam is being built in the west of the Algarve, which will be completed in 2010 and will largely increase the capacity of surface water storage. However, studies have shown that even then, water demand will be hard to meet in the long term during long periods of drought (Hidroprojecto and Ambio, 2005), if public water supply continues to depend on a single source.

Based on these foregoing, the water utility realized that in order to guarantee public water supply in the long-term, a strategy based on an integrated water resources management (IWRM) scheme is needed. New infrastructures have to be sited, designed and operated in order to have a more robust and resilient system. To accomplish those tasks, the development of a decision support system based on an optimization model is being built in the scope of a research and development (R&D) project initiated in 2005.

Aquifer system		Main aquifer lithology	Area (km^2)	Average yield (l/s)	Recharge (hm^3/ano)	Extracted volume in 2005 (hm^3)
M1	Covões	limestone, dolomite	22.56	15.5	6	0.36
M2	Almádena – Odeáxere	limestone, dolomite	63.49	5.6	16-24	0.55
M3	Mexilhoeira Grande – Portimão	limestone, dolomite, sand	51.71	8.3	10	1.18
M4	Ferragudo – Albufeira	limestone, sand	117.1	5	8	0.40
M5	Querença – Silves	limestone, dolomite	317.85	11.1	53-87	21.44
M6	Albufeira – Ribeira de Quarteira	limestone, dolomite	54.55	9.4	9	0.55
M7	Quarteira	limestone, dolomite, sand	81.19	9	12	0.13
M8	S. Brás de Alportel	limestone, dolomite	34.42	4.2	5-6	0.34
M9	Almansil - Medronhal	limestone, dolomite	23.35	7	6-7	1.92
M10	S. João da Venda - Quelfes	sand, limestone, marl	113.31	7.0; 5.5	9	0.49
M11	Chão de Cevada - Qta. João de Ourém	limestone, dolomite	5.34	6	2	0.51
M12	Campina de Faro	limestone, sand	86.39	6	10	0.13
M13	Peral – Moncarapacho	limestone	44.07	2.8	10	0
M14	Malhão	limestone, dolomite	11.83	14.7	3	0.33
M15	Luz – Tavira	limestone, sand	27.72	5.6	4	0
M16	S. Bartolomeu	limestone, dolomite	10.6	8.2	3	0
M17	Monte Gordo	sand	9.62	1.5-3.0	3	0

Table 1
Characterization of aquifer systems with regional expression in the Algarve

Under an IWRM scheme, naturally, groundwater will be a valuable resource in the Algarve. Before the existence of the MPWSS, public water supply was mainly supported by groundwater. Moreover, several studies have pointed out the advantage of the joint use of surface and groundwater for treatment requirements (e.g. Campinas et al., 2001). Unfortunately, not all wells have the same water quality and availability, which is why one of the necessary tasks of the mentioned R&D project was the realization of a screening selection of groundwater wells with sufficient quantity and quality to be integrated into the MPWSS. The aim of the current paper is to show the results of the methodology used for this purpose, thereby highlighting the qualitative aspects, though quantitative criteria, based on aquifer properties and well yields, are also considered.

Qualitative criteria are based on the construction of standard violation indices (SVIs), which are water quality indices (WQIs) that reflect the well's degree of violation of drinking water standards for a given set of variables. Such indices have been developed with the aim of rapidly combining a large quantity of chemical information of a water sample into a single value and thereby easily monitor spatial and temporal fluctuations of water quality. Moreover, WQIs are often based on specific standards such as the maximum admissible concentration (MAC) in drinking water (e.g. Harkins, 1974; Backman et al., 1998; Vieira et al., 2001, Stigter et al., 2006), constituting useful aggregation and communication tools.

Groundwater resources in the Algarve

The first hydrogeological characterisation of the Algarve was presented in the work of Trac (1981), which describes the Paleozoic unit consisting of metamorphic rocks covering an area of about 3700 km^2 in the north, and nine aquifer systems mainly supported by Jurassic, Miocene and Quaternary formations, covering an area of 1700 km^2 in the coastal strip. A detailed water balance is presented in this work, considering the separate estimation of the surface and groundwater components and an average annual precipitation calculated for the period 1941/42-1973/74 of 653 mm (Monteira and Costa, 2004). Several other detailed studies followed (e.g. Silva, 1984; Almeida, 1985; Silva, 1988), dealing with the hydrodynamics and hydrogeochemistry of the main aquifers.

The actual state of development of the Algarve hydrogeology allows the definition of 17 aquifer systems with regional importance, occupying 1074 km^2 of the referred Mesocenozoic strip. The definition of these 17 aquifer systems was proposed by Almeida et al. (2000) and their location and geometry are shown in Figure 1. Table 1 presents the main characteristics of each system, including dominant aquifer lithology, average yield and annual recharge, with an estimated total of around 200 hm^3. The most productive aquifers are built up of karstified limestones and dolomites. Municipal well yields are usually much higher than the average yields indicated in Table 1.

Monteiro and Costa (2004) and Nunes et al. (2006) provide an overview of the evolution of surface and groundwater use in the Algarve in the second half of the 20th century. The exponential rise in water demand observed in the 1960s, mainly associated to the expansion of irrigated

Table 2
Parameters involved in the SVI calculations and total number of analyses and violations

Parameter	PV	N*anal*	N*viol*	Parameter	PV	N*anal*	N*viol*
pH	6.5-9.0	2960	31	Iron (mg/l)	0.2	2172	517
Hardness (mg/l CaCO3)	500	2332	617	Manganese (mg/l)	0.05	2167	206
Conductivity (µS/cm at 20ºC)	2500	2711	144	Oxidability (mg/l)	5	2688	140
Sodium (mg/l)	200	219	17	Aluminium (mg/l)	0.2	246	0
Chloride (mg/l)	250	2911	486	Cupper (mg/l)	0.002	395	0
Sulfate (mg/l)	250	2389	33	Hydrocarbons (mg/l)	0.01	305	68
Nitrate (mg/l)	50	2797	543	PAHs (µg/l)	0.1	98	0
Nitrite (mg/l)	0.5	2645	18	Mercury (µg/l)	1	417	2
Ammonium (mg/l)	0.5	2715	27	Nickel (µg/l)	20	371	6
Total coliforms (No./100 ml)	0	1263	585	Cadmium (µg/l)	5	436	0
Fecal coliforms (No./100 ml)	0	1229	360	Chromium (µg/l)	50	427	0
Escherichia coli (No./100 ml)	0	33	5	Lead (µg/l)	10	296	3
Enterococci (No./100 ml)	0	35	2	Arsenic (µg/l)	10	418	1
Fecal streptococci (No./100 ml)	0	451	121	29 individual pesticides (µg/l)	0.1	3023	3
Clostridium perfringens (No./100 ml)	0	29	4	Total pesticides (µg/l)	0.5	184	0

PV = Parametric value for drinking water, Nanal = total number of analyses performed, Nviol = total number of violations occurred in all wells, i.e. private and municipal, between 1995 and 2005.

agriculture and the growth of tourism, was satisfied thanks to the introduction of drilling technologies that allowed the construction of thousands of boreholes in the region. These were implanted without adequate regional planning and were not supported by the existing knowledge of the region's hydrogeology. Until the end of the 20th century public water supply was locally and independently dimensioned by each of the 16 municipalities and mostly supported by groundwater.

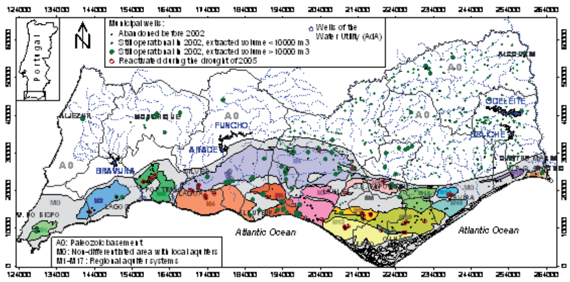

Figure 1
Location of the municipal wells and aquifer systems with regional expression in the Algarve; also shown are the main rivers and surface water reservoirs and the municipal borders and capitals

The location of the municipal wells obtained from the National Inventory of Water and Wastewater Distribution Systems of 2002 (INSAAR, 2002), is shown in Figure 1.

The efforts to abandon groundwater as a source for public water supply started in 1998, after a large investment in new infrastructures (Funcho, Odeleite dams; water treatment plants, regional distribution system) and in the rehabilitation of others ones (Beliche and Bravura dams). Due to these investments, in 2002 already 83% (57.7 hm³) of the total public water supply originated from surface water, as illustrated in Figure 2. The remaining 17% (11.9 hm³) continued to be supplied by municipal wells in those areas where the MPWSS was not operational (Figure 1). The major benefits of the use of surface water were felt in water quality and its control, which is much easier in a MPWSS than for a large number of wells operated by the municipalities.

The severe drought that occurred in 2004 and 2005 caused the complete depletion of the reservoirs in the Western Algarve, the Regional Water Utility (AdA) decided to drill 'emergency wells' in the aquifer system of Silves-Querença, the largest and most productive aquifer system. Despite the additional 11 hm³ supplied by this aquifer, the water demand could not be met by the MPWSS and formerly abandoned municipal wells had to be reactivated (their location is shown in Figure 1). In total, 42% of public water supply was supported by groundwater in 2005 (Figure 2).

As claimed by Monteiro and Costa (2004), three periods can be defined in the chronology of public water supply in the Algarve region: (1) a past period in which public water supply was almost entirely supported by groundwater; (2) a present period characterized by large investments in replacing groundwater by surface waters from dams and (3) a future period where the prevailing hydrological conditions and the conflicts between users will force the administration to define an integrated management scheme to guarantee the public water supply at basin scale.

Methods

The screening selection of groundwater wells for integration into the MPWSS is based both on quantitative and qualitative criteria. The emphasis in this paper is laid on the qualitative analysis, but quantitative criteria were also applied. For this purpose, the overall characteristics of the regional aquifer systems in the Algarve were studied based on published reports (e.g. Silva, 1984; Silva, 1988; Almeida et al., 2000) and well yields were analyzed individually when available, partly based on a previous study of Hidroprojecto (2005). In a first phase the minimum well yield considered viable for the MPWSS was 15 l/s, a criterion met by

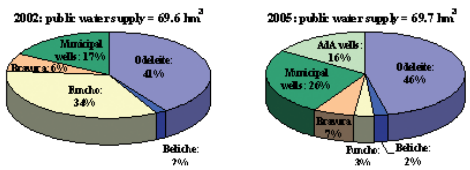

Figure 2
Surface and groundwater contributions to public water supply in 2002 (left) and 2005 (right); AdA = Águas do Algarve, Regional Water Utility; all other names refer to surface water reservoirs

73% of the wells with known yields. Subsequently, a second group of wells with lower yield was included, in order to see whether or not they satisfied the qualitative criteria. Despite a lower yield, these wells could still prove to be valuable for the MPWSS, depending on their location and on the aquifer properties. Average well yield of the two groups separated by the well yield criterion is 30 l/s and 10 l/s, respectively.

The qualitative analysis is based on chemical analyses performed in the decade 1995-2005 for the city councils and by the *Direcção Regional do Ambiente e Ordenamento do Território do Algarve (DRAOT-Alg),* currently integrated into the *Comissão de Coordenação e Desenvolvimento Regional do Algarve (CCDR-Alg)*. A total of 215 wells were included in the present study, 110 of which are municipal wells drilled for public water supply. The others are private wells inserted into the *DRAOT-Alg* monitoring network, drilled mostly for the purpose of irrigation and domestic water consumption. These are included in the study to provide a regionally more complete overview of groundwater quality in the Algarve. Based on all the available analyses, a standard violation index (SVI) was calculated for each well, for different sets of variables, based on the associated drinking water standards, represented by the parametric values (PVs) of the EU Drinking Water Directive (98/83/CE). The SVI is calculated in the following way:

$$\mathrm{SVI}_{i(j_1,j_2,...,j_p,t_0-t_u)} = \frac{N_{i,viol}(j_1,j_2,...,j_p,t_0-t_u)}{N_{i,anal}(j_1,j_2,...,j_p,t_0-t_u)}$$

Where SVI_i is the standard violation index of observation point (well) i, j_1 is the first variable of the set, j_2 the second variable, etc., t_0 the date of the first analysis considered, t_u the date of the last analysis considered, $N_{i,viol}$ the number of violations that occurred and $N_{i,anal}$ the total number of analyses performed, for all the involved variables ($j_1, j_2, \ldots$) during time interval t_0-t_i at well i. The SVI varies between 0 and 1, i.e. between 0% and 100% of drinking water standard violations. The calculation algorithm was developed in such a way that the SVI_i is not calculated when records of one of the involved variables are lacking. Table 2 lists the parameters that were included in the index calculations. Five different SVIs were developed, based on different sets of variables, as shown in Table 3.

The first index, $\mathrm{SVI}_{\mathrm{Tot}}$, includes all the parameters of Table 2 and was created with the aim to provide a general overview of the total number of analyses performed between 1995 and 2005 and the total number of violations occurred. $\mathrm{SVI}_{\mathrm{Toxic}}$ is based on toxic substances and includes the bottom nine parameters of right column of Table 2. Any violation revealed by this index results in the exclusion of the corresponding well for drinking water purposes and should be analyzed in more detail. Fortunately, only very few violations are detected.

$\mathrm{SVI}_{\mathrm{Microbiol}}$ is an indicator for microbiological contamination and the type and/or level of disinfection required during water treatment. In fact, groundwater used for drinking purposes in the region is only treated by disinfection, usually chlorination. As microbiological contamination of groundwater is frequent, it is perhaps more useful to indicate the degree of contamination. Council Directive 75/440/EEC concerning the quality required of surface water intended for the abstraction of drinking water, defines three categories of water treatment (A1, A2, A3) from simple physical treatment and disinfection to intensive physical and chemical treatment. The same classes may also apply for groundwater, as Portuguese legislation indicates that groundwater intended for the abstraction of drinking water should at least satisfy the maximum recommended concentrations (MRC) for surface waters and maximum admissible concentrations (MAC) of treatment class A1. Table 4 presents the MRC established for three microbiological parameters for each treatment class. Although not entirely correct, analyses of *Escherichia coli* and enterococci were considered together with those of fecal streptococci. The table also indicates the percentage of groundwater samples belonging to each class.

The $SVI_{NO3,Cl}$ combines two parameters that have several aspects in common. First of all, both contaminants are typical indicators of a disturbance of the natural state of groundwater, often due to human activities. For instance, agricultural practices have a large impact on both parameters in the region, due to excess fertilization and groundwater extraction for irrigation (e.g. Stigter et al., 2006). Second, neither nitrate nor chloride is removed from water in conventional treatment plants such as those that exist in the Algarve. The reason is that treatment is designed for surface water, which rarely contains high concentrations of these parameters. Therefore, violations of the MAC in principle impair the use of the well for drinking water, though groundwater may be mixed with surface water to obtain acceptable levels for public supply. Nitrate in drinking water is generally considered to constitute a health hazard for babies and young infants. Its toxicity is mainly attributable to the reduction to nitrite and associated to methaemoglobinemia (WHO, 1996). However, several recent studies question the importance of nitrate in drinking water as a risk factor for methemoglobinemia (e.g. L'hirondel and L'hirondel, 2002; Addiscott, 2006). Chloride is an indicator of salinity, which in high concentrations can give rise to bad taste and is indirectly associated with hypertension.

In the case of $SVI_{Fe,Mn}$, the index indicates the need of iron and manganese removal from groundwater for public supply, increasing the treatment costs. When oxidation to iron (III) and manganese (IV) states occur, precipitates are formed that provide the water a dark, turbid aspect. Both parameters are treated at water treatment plants, though they can form stable complexes with humic substances in water that can be more resistant to oxidation. As far as is known, there are no health problems related to iron and manganese for humans, but their presence in public water supplies can create serious problems. In distribution systems, they can cause difficulties by supporting the growth of iron bacteria, whereas during domestic use, they interfere with laundering operations, impart objectionable stains to plumbing

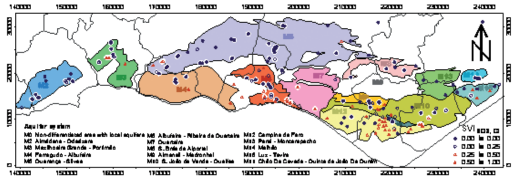

Figure 3 Spatial distribution of $SVI_{NO3,Cl}$ for municipal wells (white background) and private wells in the main aquifer systems of the Algarve

fixtures and impart a taste to water (for iron) detectable at very low concentrations (Sawyer et al., 2003).

High values of hardness in water supplies may also affect its acceptability to the consumer in terms of taste and scale deposition (WHO, 1996), and result in the use of higher amounts of laundry detergents. Groundwater in the region naturally acquires high levels of hardness, since the most important aquifers are supported by carbonate rocks. Table 5 presents the classification of hardness according to Sawyer et al. (2003) and the percentage of

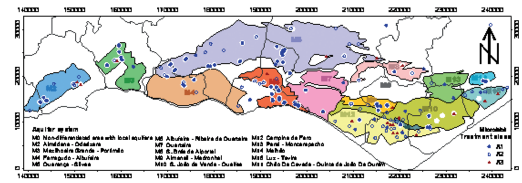

Figure 4 Spatial distribution of recommended treatment class for municipal wells (white background) and private wells in the main aquifer systems of the Algarve, regarding the highest observed level of microbiological contamination

groundwater samples that falls in each class. Almost 90% of sampled groundwater is classified as very hard, whereas 27% exceed the former EU MAC. No PV is defined for hardness or any of its derivatives in the current EU Drinking Water Directive.

At a first stage, very strict criteria were defined for the selection of the municipal wells with potential to be

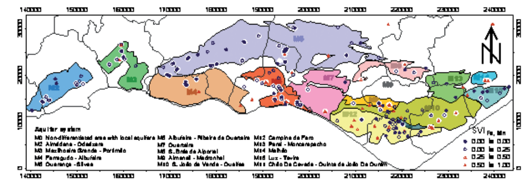

Figure 5 Spatial distribution of $SVI_{Fe,Mn}$ for municipal wells (white background) and private wells in the main aquifer systems of the Algarve

integrated into the MPWSS: i) all samples of the well belong to class A1 of required microbiological treatment and ii) SVI_{toxic}, $SVI_{NO3,Cl}$ and $SVI_{Fe,Mn}$ are equal to 0, i.e. no violations are observed. In other words, the wells selected based on these criteria, only required disinfection before obtaining the status of completely potable and acceptable for public water supply. However, not many wells satisfy these criteria, mainly due to high iron and manganese concentrations and microbiological contamination of groundwater. Therefore, the criterion level for $SVI_{Fe,Mn}$ was increased to 0.25, which meant that wells with a maximum of one PV violation in every four iron or manganese analyses where accepted for public water supply. A careful study of the individual data revealed that half of the wells selected on this criterion, have a $SVI_{Fe,Mn}$ below 0.1, i.e. less than one violation in ten analyses. The reason of loosening the $SVI_{Fe,Mn}$ criterion is twofold. First, elevated concentrations in groundwater are caused by natural rather than human factors. Second, concentrations are reduced during conventional water treatment. The hypothesis of loosening the criterion for $SVI_{NO3,Cl}$ was initially also considered, but later on rejected, based on the same reasoning used for $SVI_{Fe,Mn}$, with opposing conclusions. High concentrations of nitrate and chlorine are due to human impact in the majority of cases, whereas their removal during conventional water treatment does not occur.

Results and discussion

The spatial distribution of $SVI_{NO3,Cl}$ in the main aquifer systems of the Algarve is shown in Figure 3, both for municipal and private wells that are integrated in the monitoring network of DRAOT-Alg. Since only municipal wells with zero index values are considered for integration into the MPWSS, the map already provides a good overview of the aquifer systems that are most interesting from a qualitative point of view. The highest index scores (worst water quality) are observed in the coastal aquifers M6 (Albufeira – Ribeira de Quarteira), M12 (Campina de Faro) and M15 (Luz – Tavira). A more detailed data analysis reveals that the in aquifer M6, mostly municipal wells are affected, and that chloride, i.e. salinity is the dominating factor influencing the $SVI_{NO3,Cl}$. This proves that groundwater extraction has led to saltwater intrusion, with seawater as the most likely source, though natural sources (i.e. connate water, evaporate dissolution) may not be excluded without a detailed hydrogeochemical study. The same phenomenon explains the higher scores for the wells in the southern sector of aquifer system M3 (Albufeira – Ribeira de Quarteira) and the eastern sector of aquifer system M2 (Almádena – Odeáxere). On the contrary, wells in aquifers M12 and M15 are mostly private and their high scores related to both nitrate and chloride. The principal diffuse source of nitrate is the use of mineral fertilizers in agriculture. In addition, irrigation with locally extracted groundwater induces a

Standard Violation Index	Definition	t0-tu	Nanal	Nviol	%viol
SVIAll	All parameters	1995-2005	38362	3939	10.3%
SVIToxic	Toxic parameters	1995-2005	5670	15	0.3%
SVIMicrobiol	Microbiological parameters	1995-2005	3040	1077	35.4%
SVINO3,Cl	Nitrate and Chloride	1995-2005	5708	1029	18.0%
SVIFe,Mn	Iron and Manganese	1995-2005	4339	723	16.7%

Table 3
Definition of Standard Violation Indexes (SVIs) used in the present study

groundwater cycle that gradually increases the nitrate concentrations along with the overall groundwater salinity, especially in semi-arid regions such as the Algarve. The problem has been officially recognized for both aquifer systems, as they include the only two nitrate vulnerable zones designated in the Algarve in compliance with the Nitrates Directive 91/676/EEC. The lowest $SVI_{NO3,Cl}$ scores (best water quality) are found in aquifer systems M5 (Querença – Silves), except for its westernmost sector, M9 (Almansil – Medronhal), M14 (Malhão), the western sector of M2 and the northern sector of M3.

Parameter	Treatment class A1		Treatment class A2		Treatment class A3	
	MRC	Frequency	MRC	Frequency	MRC	Frequency
Total coliforms (No./100 ml)	50	81.2%	5000	16.8%	50000	2.0%
Fecal coliforms (No./100 ml)	20	88.3%	2000	11.0%	20000	0.7%
Fecal streptococci (No./100 ml)	20	89.4%	1000	9.8%	10000	0.8%

Table 4
Maximum recommended concentrations (MRC) of treatment classes defined for surface water intended for the abstraction of drinking water and frequency of occurrence in groundwater samples

All these are carbonate aquifers, with high recharge rates and groundwater velocities, and often located more inland, protected from seawater intrusion.

Leaching of domestic effluents can be an important point source of nitrogen in areas outside the larger cities, where wastewater drainage systems are absent. Septic tanks are not always used as an alternative and when they do exist, they may be poorly constructed or maintained. This is clearly revealed in the map of Figure 4, which depicts the spatial distribution of recommended treatment class for the wells, regarding the highest observed level of microbiological contamination. Many of the wells in aquifers M12 and M15 belong to class A2 or even A3. This fact has provoked a long and still ongoing debate between the Ministries of Agriculture and Environment as to the origin of nitrate in groundwater. Of the municipal wells 80% reveal some degree of microbiological contamination, but only 30% have shown concentrations above the MRC of treatment class A1. Contamination is mostly of domestic origin, though some intensive and extensive livestock farming is practiced in small areas of the Algarve.

The spatial distribution of $SVI_{Fe,Mn}$ in the region's groundwater, presented in Figure 5, appears to be rather irregular. Many aquifer systems present a large range of index scores. The concentration of iron and manganese in groundwater is mainly influenced by aquifer lithology and redox conditions, as both elements are common constituents of anoxic groundwater (Appelo and Postma, 1994). Consequently, a negative correlation is observed with nitrate concentrations, which is partly revealed when comparing Figure 5 to Figure 3, for instance, in the western sector of aquifer system M12.

Based on the calculated index scores, the wells were distributed among six quality classes, as illustrated in Figure 6. The first class represents the highest quality and includes wells extracting groundwater that after a basic disinfection (class A1) are ready to be used for drinking water purposes.

Wells of the second and third class only require additional iron and manganese removal ($SVI_{Fe,Mn}$ >0.25) or disinfection (class A2 and A3), respectively, whereas wells of class four require both. Hence, wells of classes 2, 3 and 4 can all be used in the MPWSS as long as extracted groundwater is previously diverted to water treatment plants or receives the required treatment *in situ*. The costs involved in the latter scenario are currently being studied. Finally the last two classes include wells that are not considered for drinking water, either due to the presence of nitrate and chloride (class 5) or toxic substances (class '0').

It should be referred that the presence of toxic substances, which involve lead, arsenic, nickel, mercury and pesticides, was only detected in 15 samples and never more than once in the same well, with one exception, where lead was found twice in the same well in a short period of time. Nickel was found in six samples, but only on two different dates, whereas mercury was found in two samples on the same date. Though a more detailed study is required, the low number of samples most likely indicates the occurrence of local accidental spills, without any long-term consequences. In fact, three municipal wells with a SVI_{toxic} >0 and therefore not considered for public supply in this study, are currently still operational, located in the largest aquifer system (M5) and with a total well yield of 111 l/s.

The private wells were included in this study in order to provide a more complete overview of groundwater quality in the region. They present an overall lower groundwater quality, mainly attributable to high $SVI_{NO3,Cl}$ scores (Figure 6), which is a logical consequence of their location and purpose (irrigation). For the MPWSS only municipal wells should be considered. Figure 7 indicates the cumulative well yield attributable to the four quality classes that permit the use for drinking water and hence integration into the MPWSS, after the necessary treatment measures referred for each class. The wells were further subdivided according to the quantitative criterion level of 15 l/s. For the sake of a better comprehension of the total well yields, these are compared to the average public water demand in the region (2000 l/s).

It can be observed that based solely on the current screening selection procedure (i.e. not considering other aspects, such as sustainable yield, infrastructure, etc.) 1000 l/s or 50% of the average public water demand could be obtained from groundwater after disinfection, whereas an additional 600 l/s could be included after iron and manganese removal and additional disinfection. These values are somewhat lower than initially presented, mainly because some wells with low non-zero $SVI_{NO3,Cl}$ values formerly considered, have now been excluded. On the other hand, total yield is higher when considering the referred active wells with non-zero SVI_{toxic} scores.

Figure 8 shows the location of the selected wells, thereby also indicating the most important aquifers to be considered for public water supply, namely M2, M3 (northern sector), M5, M8, M9 and M14. It was already seen that M5 is by far the largest, most productive and hence most important aquifer system in the region, supplying 76% of the groundwater volume and 31% of the total water volume for public supply in 2005 (Table 1). Though the other mentioned aquifers are of a much smaller dimension, they can be extremely useful. For instance, groundwater of aquifer M14 and the northern sector of aquifer M3 could be diverted to the nearby located treatment plants, where they could be mixed with surface water prior to treatment. The typical natural characteristics of groundwater, such as high degree of hardness and low turbidity, makes it extremely advantageous for

Table 5
Hardness classes (Sawyer et al., 2003) and frequency of occurrence in groundwater samples

Class	Hardness (mg/l)	Hardness degree	Sample frequency
1	0-75	Soft	2.1%
2	75-150	Moderately hard	3.5%
3	150-300	Hard	7.2%
4	300-500	Very hard	60.8%
5*	> 500	Above MAC	26.5%

mixing with surface water, with regard to treatment requirements (e.g. Campinas et al., 2001). In the project, simple hydrochemical models are being used to assess water quality changes driven by mixing, especially those concerning carbonate equilibria.

Final considerations

The standard violation indices (SVIs) created in this study have shown to be very useful tools for the spatial monitoring of groundwater quality and potability. Their application is simple and straightforward and based on well-established drinking water guidelines, so that their interpretation is unbiased. Naturally, the aggregation also implies a loss of information, and trends of decreasing groundwater quality may be hidden if parametric values have not yet been exceeded. The SVIs used in the present study all concern parameters that are simultaneously indicative for groundwater chemistry and drinking water quality, so that the selection criteria are valid and representative for this water source. For other water sources, such as surface water, other quality parameters may be more representative, therefore requiring the choice of different SVIs and selection criteria.

The construction of SVIs led to a screening selection of more than 40 municipal wells that could be included in the MPWSS and used for public water supply after disinfection, and an additional 25 wells that could be included after iron and manganese removal and additional disinfection. This screening selection is very useful for the decision support system currently being developed, as it allows a reduction of dimension in the non-linear mixed integer model that will be solved, while not eliminating the most important alternative groundwater sources for the MPWSS. The decision support system also integrates groundwater simulation models, and final selection of wells and pumping policies will be assessed, both in terms of costs and safe yield considerations. ●

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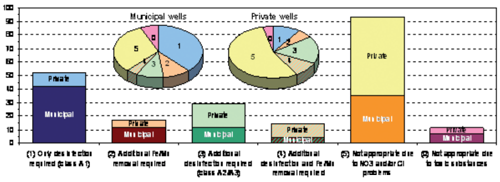

Figure 6
Results of SVI calculations and application of criteria for municipal and private wells

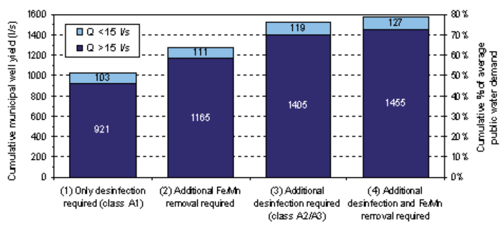

Figure 7
Absolute and hypothetical relative values of cumulative well yield with increasing treatment requirements; relative values are based on continuous pumping and compared to the average public water demand in the region

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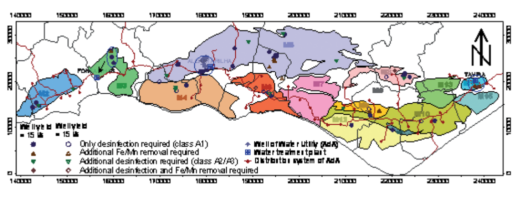
Figure 8
Location of municipal wells with potential for integration into the MPWSS, selected on the basis of well yield and qualitative criteria indicating different treatment requirements; also shown in the distribution system of the Water Utility; circles indicate wells whose groundwater could be diverted to treatment plants located nearby



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