Infiltration in Sewer Systems: Multi-Criteria Comparison of Investment / Rehabilitation Strategies

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Abstract
Within the FP5 European APUSS project (Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems), a methodology has been proposed to account for environmental, technical and economic impacts of infiltration or exfiltration on sewer systems, treatment plants and receiving waters, and to evaluate the consequences of possible investment / rehabilitation strategies. The multi-criteria method Electre III is used to compare and to rank the various strategies, as this method has a high potential adaptability to diverse contexts and objectives. An example of application of the proposed methodology is given for a 245 ha residential catchment equipped with a combined sewer system, including scenarios with different infiltration rates. It shows that the methodology is applicable, but also that validated and site specific information (data, measurements, calibrated models, etc.) is necessary in order to carry out a valuable analysis. Results shall be reviewed carefully and the final decision making process should take into account the context of the study. There is no unique best investment strategy, but several options may be considered depending on priorities and criteria of the sewer operator. The methodology is general, but results of the case study are site specific and cannot be extrapolated.

Keywords
Infiltration, multi-criteria analysis, rehabilitation, sewer systems

INTRODUCTION

Infiltration and/or exfiltration (I/E) in sewer systems have technical, environmental and economic impacts. Sewer operators have to make decisions and choices among several possible investment / rehabilitation strategies aiming to solve the problems related to I/E. In most frequent cases, the comparison of the possible strategies is based on a traditional cost-benefit approach, which consists to minimise the costs of investment and operation for an expected given benefit. Two of the main limitations in such an approach are the difficulty: i) to evaluate all criteria in monetary units (e.g. what is the cost in Euros of any kg of COD discharged into a river by a wastewater treatment plant (WWTP) overloaded by infiltration?), and ii) to take into account some criteria that can not be easily calculated, like e.g. environmental aspects.

The choice of any investment strategy dealing with I/E phenomena should obviously include environmental, technical and economic aspects. Within the FP5 European APUSS project - Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems (see http://www.insa-lyon.fr/Laboratoires/URGC-HU/apuss), a specific work package (Baer *et al.*, 2005) has been devoted to a methodology aiming to help practitioners in the evaluation and the comparison of investment / rehabilitation strategies. The two main objectives were: i) to propose a general methodology based on an integrated and multi-criteria approach to compare and rank strategies to remedy I/E problems; ii) to illustrate the application of this methodology to a semi-virtual case study.

This paper presents successively: i) the methodology, ii) the description of the sewer system used for the case study, iii) the evaluation of the impacts of infiltration, iv) the investment / rehabilitation strategies, v) the multi-criteria comparison of the strategies and some results of the case study.

It should be clearly emphasised here that the most important point in this paper is the methodology itself, which can be applied by any operator with his/her own information and with necessary adaptations. The semi-virtual case study is only given to illustrate how the methodology can be applied to a specific case, with site specific simplifications and hypotheses. Consequently, the conclusions drawn from the case study should be neither generalised nor extrapolated.

DESCRIPTION OF THE METHODOLOGY

The methodology is represented in Figure 1, with 8 main steps. Infiltration and exfiltration in sewers may have numerous impacts on the urban water system - see e.g. Neitzke (2002) for a review. The inventory and the evaluation of these impacts (step 1) are fundamental in order to obtain an exhaustive view of the different aspects and to avoid neglecting any of them. For any specific catchment, all impacts have to be checked (are they all pertinent in this particular catchment?) and evaluated (flows, volumes, transfer of pollutants, etc.) by means of appropriate measurements and modelling. Of course, the quality of this evaluation is a key element for the quality of the following steps in the methodology. The necessary efforts have to be devoted to get and elaborate the required knowledge about phenomena and impacts. Impacts will then be expressed by means of quantitative criteria (each one with its own unit) if data and models are available, otherwise by means of qualitative criteria, e.g. evaluation grades based on operator expertise and estimation (step 2) for their evaluation and for the comparison of investment strategies.

A review of all possible investment / rehabilitation strategies should be made (step 3). Regarding infiltration, the strategies may concern e.g. the sewer pipes (rehabilitation), and/or the WWTP (e.g. larger treatment capacities) and/or CSO storage tanks (larger tank capacities). Regarding exfiltration, only rehabilitation of sewer pipes may solve the negative impacts on soil and groundwater generated by exfiltration. After review, each possible strategy should be defined in detail and evaluated (step 4). Possible rehabilitation technologies (RTs) have to be selected according to their technical specifications and to their costs (see e.g. Villanueva *et al.*, 2004 who made a review of more than 70 techniques in the CARE-S project, O'Brien and Gere, 2001; Frehmann, 2004; RERAU, 2004; Freni *et al.*, 2005).

After the choice of possible additional criteria (step 5) including e.g. the expected life time of the RT (Delleur *et al.*, 1998; Orditz, 2004) or the serviceability of the sewer system (Ewan Associates and Mac Donald, 2001) or any other criterion considered as pertinent for the case which is studied, all quantitative criteria have to be calculated (by simple calculations or more elaborated simulation models) and all qualitative criteria have to be estimated (by expertise, empirical knowledge, etc.) (step 6). The analysis of the results and the ranking of the strategies are carried out by means of a multi-criteria approach (step 7).

Among the several existing multi-criteria methods, the Electre III method (Roy, 1978; Vincke, 1992) is widely used and accounts for uncertainties in the evaluation of the performance indicators or of criteria well appropriate for environmental studies, because of the high uncertainties in data and results (Bertrand-Krajewski *et al.*, 2002). Contrary to traditional cost-benefit approaches, all criteria in Electre III are expressed with their own natural units, avoiding the problems due to averaging of or the compensation for the criteria. In order to rank the strategies, Electre III needs weights and thresholds values which remain and are accepted to be subjective. However, as it may have a great influence on the final results, the proposed solutions have to be reviewed critically, e.g. by means of a robustness analysis, before making the final decision (step 8).

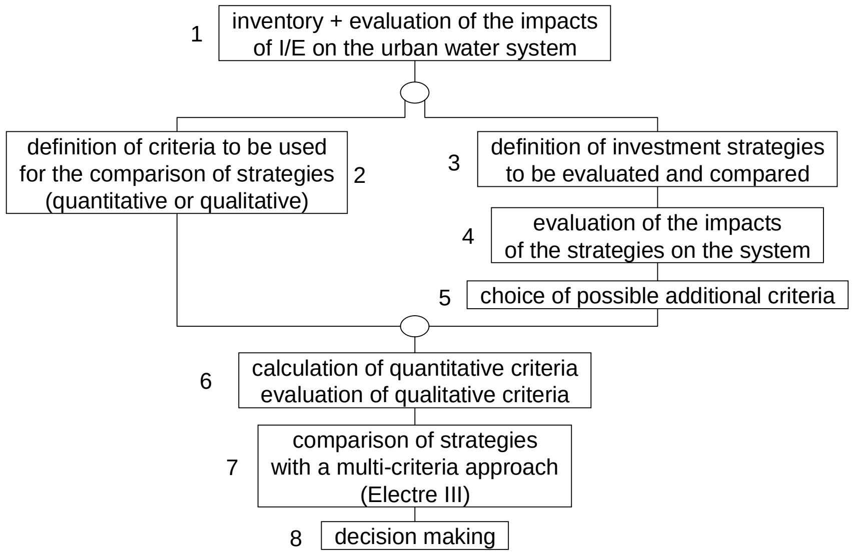

Figure 1. Methodology for definition, comparison and choice of investment / rehabilitation strategies regarding infiltration / exfiltration based on a multi-criteria analysis.

DESCRIPTION OF THE ECULLY SEMI-VIRTUAL SEWER SYSTEM

The above methodology has been tested, for demonstration purposes, on a semi-virtual case study based on the Ecully catchment, France. Ecully is a 245 hectares urban catchment in the western suburbs of Lyon. It is one of the experimental catchments of the OTHU project (http://www.graie.org/othu/). The habitat is mostly residential and the imperviousness of the catchment is evaluated to 46 %. The drainage system is a combined system with a 0.027 m/m mean slope. There is no WWTP at the outlet of the actual catchment, but a trunk sewer leading the effluents to one of the two largest WWTPs in Lyon. For the purpose of this case study, a virtual WWTP has been introduced, designed and simulated by means of the ASIM software developed at EAWAG (Gujer and Larsen, 1995). In order to limit the impact of CSOs, a virtual CSO storage tank has also been introduced in the case study. All components are schematized in Figure 2, with some basic elements of information. Available data from the OTHU monitoring station and from measurement campaigns are: i) 2 years of discharge measurements at the catchment outlet, recorded with a 2 min time step, ii) 15 years of rainfall data from the nearest raingauge located in Champagne-au-Mont-d'Or, recorded with a 6 min time step, iii) 8 measurement campaigns carried out during dry weather, with hourly data on suspended solids, COD and TKN concentrations, iv) 15 measurement campaigns carried out during storm weather, with data on suspended solids, COD and BOD concentrations.

Both the rainfall - runoff process over the catchment and the flow propagation in the sewer network are simulated by means of initial and continuous rainfall losses functions and by means of a single linear reservoir. The model has been calibrated with 10 rainfall events and validated with 5 other events. The mean dry weather foul sewage flow without infiltration is equal to 1900 m^3/day. The WWTP is an activated sludge plant with biological nitrogen removal (nitrification-denitrification). The design has been calculated for a maximum inflow Q_{max} equal to 3 times the dry weather flow DWF, for an influent temperature of 13°C and for a maximum nitrogen concentration in the effluent equal to 10 mg N/L (i.e. 83 % removal), which leads to a COD removal rate equal to 95 %. Based on measurement campaigns, foul sewage and surface runoff mean concentrations of COD and TKN are respectively equal to 519 and 224 mg O_2/L, and 59 and 19 mg N/L. In case of overflow, the excess flow is temporarily stored in the CSO tank. If the CSO tank is full, the effluents are discharged directly into the receiving water. The water stored in the tank is then pumped towards the WWTP, its storage duration being less than 24 hours, in order to avoid septicity and its detrimental consequence on the WWTP. If the storage duration is longer than 24 h, the water is discharged into the receiving water. These rules have been defined to simplify the case study. For real systems, other and more complex rules may be used.

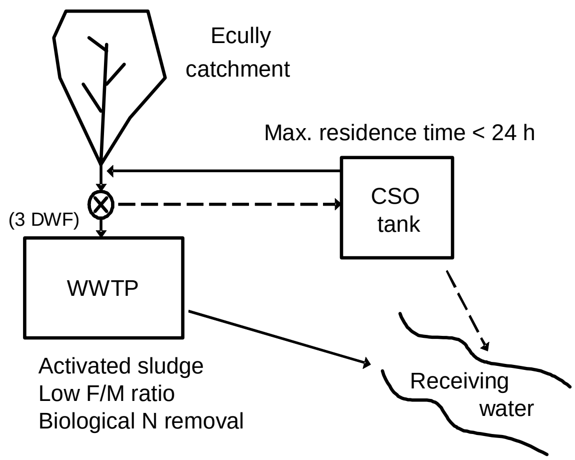

Figure 2. Components of the Ecully semi-virtual case-study.

The infiltration ratio IR is defined as the percentage of infiltrated water compared to the dry weather foul sewage. In the absence of storm event, IR = 50 % corresponds to a daily volume of infiltrated water equal to 50 % of the daily foul sewage volume. Seven simulation series (scenarios) have been carried out over a 15 years long period (to account for annual variability) including both dry and wet weather conditions, with infiltration ratios of 0, 25, 50, 75, 100, 150 and 200 %. The reference simulation series (scenario A) is calculated with IR = 0 %, with a well designed WWTP and without CSO tank. All simulations are carried out with a 6 minute time step to account for storm events, and results are then recalculated for daily time steps. The results of each simulation series are i) economic criteria: operation costs (Euro/year) and ii) environmental criteria: annual COD and total nitrogen (NGL) loads discharged into the receiving water by the WWTP (treated effluent) and by the CSO structure (untreated effluent) (kg/year). It was assumed that i) infiltration of clear water does not bring any pollutant into the sewer system and does not change the influent temperature which follows a sinusoidal function over the year, and ii) infiltration occurs only between January and July, which corresponds to the high groundwater level period. Annual volume and pollutant loads treated by the WWTP are stable for all 15 years. Consequently, the WWTP operation and the impacts of infiltration have been simulated only for year n° 1, assumed to be representative of the 15 year period. However, the total non treated pollutant load varies significantly from one year to another one: the non treated COD load discharged in the year 15 is four times higher than the load discharged in the year 9 and two times higher than the average year. In order to take into account this significant variability, three years have been analysed specifically: year n° 1 as an average rainfall year (521 mm/year), year n° 9 as the minimum rainfall year (246 mm/year) and year n° 15 as the maximum rainfall year (828 mm/year).

IMPACTS OF INFILTRATION ON POLLUTANT LOADS AND ENERGY

Infiltration increases the hydraulic loads in the sewer system, which leads to i) higher annual energy consumption for the pumping station and the WWTP operation and ii) more frequent discharges of non-treated pollutant loads due to more frequent combined sewer overflows. Infiltration also increases the annual pollutant loads discharged by the WWTP due to the decrease of the WWTP efficiency regarding the carbon and nitrogen removal. Synthetic results are given in Table 1 for the year n° 1 (detailed results are given in Baer *et al.*, 2005).

Table 1. Increase, for year n° 1, of annual COD and NGL loads (kg/year) discharged into the receiving water vs. infiltration ratio IR. Reference value = 1 for scenario A with IR = 0 %.

IR (%)	0%	25%	50%	75%	100%	150%	200%
Total COD load emitted in the receiving water (kg COD/year)	76005	77129	78879	80626	83503	87949	93866
Total NGL load emitted in the receiving water (kg COD/year)	12385	12617	13012	13315	13662	14298	15498
Total COD load with infiltration / total COD load without infiltration (scenarion A)	1.00	1.01	1.04	1.06	1.10	1.16	1.23
Total NGL load with infiltration / total NGL load without infiltration (scenarion A)	1.00	1.02	1.05	1.08	1.10	1.15	1.25

With IR = 150 %, there is an increase of respectively 16 % and 15 % of the mean annual COD and NGL loads discharged into the receiving water, due to both more frequent CSOs and the decrease of the WWTP nitrogen removal efficiency from 83 % to 76 %. It also appears that impacts of infiltration vary from one year to another one depending on the rainfall variability. For example, the total annual COD loads discharged into the receiving water with IR = 200 % compared to the scenario A (without infiltration) is higher for the year 15 than for the year 1 (data not shown here). Consequently, meaningful changes in total annual pollutant loads may vary with the studied year, which can affect the decision. One of the advantages of Electre III is that this kind of uncertainty and variability can be accounted for by means of indifference and preference thresholds. However, the operator must be aware of this variability and has to compare the results for several years before making the decision regarding investment strategies.

The energy consumption includes i) the pumps at the WWTP inlet, ii) the pumps for sludge and nitrate recirculation, iii) the aeration by small air bubbles diffusers, iv) the mixing of anoxic and aerobic tanks. Some results are given in Table 2. The difference in the total annual energy consumption becomes significant from IR = 150 % (ratio 1.10). The additional costs for the WWTP operation reach 13 % for IR = 200 %. In the Ecully case-study, with IR = 25 % and 50 %, impacts of infiltration are low on both the pollutant loads emitted by the WWTP and the energy consumption for all 15 years. No rehabilitation or investment is really needed. From IR = 75 % to 150 % depending on the year (this illustrates the significance of inter-annual variability), negative impacts on pollutant loads and on operation costs may lead to consider a rehabilitation of the drainage system. Of course, many investment / rehabilitation strategies may be defined. Some strategies will be chosen and compared in the following sections.

Table 2. Total relative annual energy consumption (reference value = 1 for scenario A) and total annual costs in Euros vs. infiltration ratio IR.

IR (%)	0%	25%	50%	75%	100%	150%	200%
Energy for pumping station	1.00	1.11	1.23	1.34	1.45	1.67	1.87
Energy for recirculation	1.00	1.05	1.11	1.16	1.21	1.32	1.41
Total energy	1.00	1.02	1.04	1.05	1.07	1.10	1.13
Total energy costs (Euros/year)	19770	20093	20466	20781	21100	21737	22336
Additional costs due to infiltration (Euros/year)	0	323	696	1011	1330	1967	2566

POSSIBLE INVESTMENT / REHABILITATION STRATEGIES

Three strategies have been chosen and analysed: i) investment in higher treatment plant capacities in order to account for infiltration, e.g. to have the same efficiency than without infiltration, ii) investment in rehabilitation of the sewer system, and iii) a mixed investment: renovation of 50 % of the infiltrating sewer pipes and investment in upgrading the WWTP.

Regarding the rehabilitation of the sewer system, three rehabilitation technologies (RTs) were selected for repair (injection), renovation (thermosetting resin impregnating a prefabricated flexible tube) or replacement (traditional trench). Average investment costs have been determined from literature and expertise. Facing the lack of data regarding the detailed actual structural state of sewer pipes in Ecully, the following hypotheses have been made: i) infiltration occurs only in pipes located in the river aquifer, and ii) infiltration is diffuse and occurs along all pipes located in the aquifer. Another important hypothesis is that rehabilitating 100 % of the infiltrating pipes will solve 100 % of the infiltration problems. This optimistic hypothesis should be considered with caution because groundwater may find other ways to enter the sewer systems (HC, manholes, etc.).

Regarding WWTP upgrading, infiltration impacts are easily compensated with the scenario A WWTP until IR = 75 % by increasing only the nitrate recirculation for a better denitrification. From IR = 100 %, the maximum limit for nitrate recirculation is reached (4 times dry weather flow), and the volume of the biological tanks has to be increased in order to fully account for infiltration (Table 3). As the secondary clarifier is designed according to hydraulic constraints, its size increases with IR. For IR values higher than 100 %, the impacts of infiltration on the WWTP are very significant. Regarding the CSO tank, simulations with specific volumes of 20, 50 and 100 m^3/ha revealed that, in Ecully with a WWTP designed for 3×DWF, the CSO tank had a negligible effect. As a consequence, the CSO tank has not been kept as a valuable element in the strategies to be analysed.

Table 3. Increase of the relative sizes of biological tanks and of the clarifier vs. IR.

IR (%)	0%	25%	50%	75%	100%	150%	200%
Biological tank volume	1.00	1.00	1.00	1.00	1.00	1.25	3.50
Secondary clarifier volume	1.00	1.14	1.41	1.69	1.98	2.08	2.36

COMPARISON OF THE STRATEGIES

The three strategies have been compared by means of 5 criteria: annual COD load, annual NGL load, annual operation costs, investment costs and total annual costs (operation + investment). Figure 3 shows the results obtained for NGL loads. Investment in higher WWTP capacities represents the best solution: NGL loads are 13 to 33 % lower than with sewer rehabilitation. Rather similar results are obtained for COD loads. Regarding operation costs, WWTP upgrading is the worst solution and sewer rehabilitation appears as the best one.

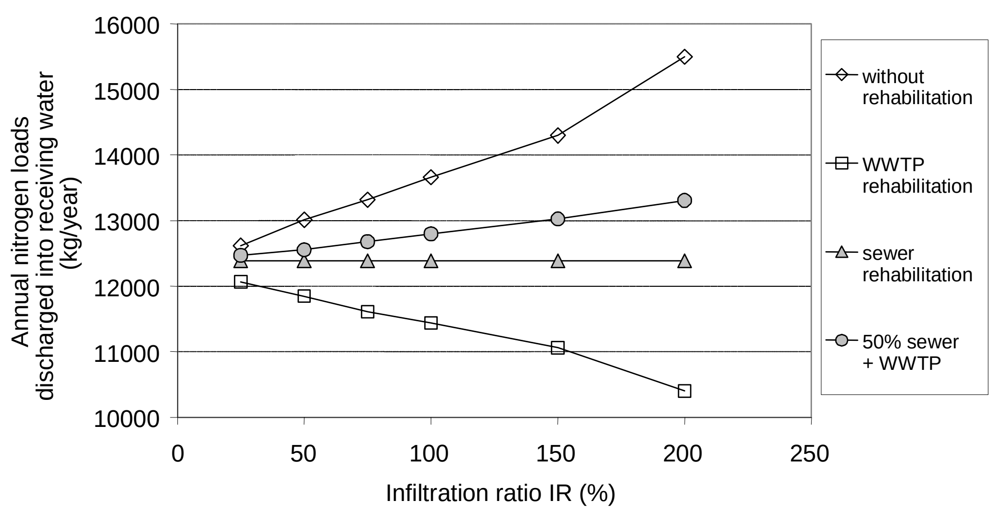

Figure 3. Annual NGL loads discharged into the receiving water vs. IR and strategy.

A complete analysis of all results (not shown here) reveals that none of the three strategies appears as the best one for all criteria. Each scenario with IR ≥ 75 % has then been analysed by means of Electre III with the weights and thresholds defined in Table 4. Of course, the choice of weights and thresholds depends on each operator and on each case. An analysis of the robustness and of the sensitivity of these parameters should be carried out in order to check if the calculated ranking is stable or not. In the present case, the results appeared rather stable. The application of Electre III leads to the results given in Table 5.

With IR = 75 %, the preferable strategies, in decreasing order, are successively “no investment”, WWTP upgrading, repair of sewer pipes, renovation of sewer pipes and replacement of sewer pipes. With IR = 150 %, the preferred strategies, in decreasing order, are successively repair of sewer pipes, WWTP upgrading with same rank as renovation of sewer pipes, “no investment”, renovation of 50 % of sewer pipes mixed with WWTP upgrading, and replacement of sewer pipes. Repair appears as the preferable solution because it efficiently reduces pollutant loads and it is a cheap investment. The “no investment” strategy is acceptable for low IR, but is the worst solution for high IR due to the greater pollutant loads discharged into the receiving water.

Table 4. Set of Electre III parameters without accounting for sewer serviceability.

	Environmental criteria		Economic criteria		
Criterion	Total COD load (kg/year)	Total nitrogen load (kg/year)	Operation costs (€/year)	Investment costs (€)	Total annual costs (€/year)
Weight	3	3	2	2	2
Indifference threshold	5 %	5 %	2000 €	50 000 €	10 000 €
Preference threshold	10 %	10 %	5000 €	100 000 €	20 000 €

Table 5. Final ranking of the investment strategies by Electre III.

IR (%)	Ranking results					
75	without	► WWTP	► repair	► renovation	► replacement	
100	repair	► WWTP	► without	► renovation	► replacement	► 50 % R
150	repair	► WWTP or renovation	► without	► 50 % R	► replacement	
200	repair	► WWTP or renovation	► without or replacement		► 50 % R	

“Without” means “no investment” and “50 % R” means the mixed investment strategy.

CONCLUSION

A general methodology is proposed to assess environmental, technical and economic impacts of infiltration (or exfiltration) on urban water systems, and to evaluate the consequences of possible investment / rehabilitation strategies. The multi-criteria method Electre III is used to compare and rank the strategies. The Ecully semi-virtual case study illustrates the application of the methodology. It shows that the methodology is actually applicable, but also that validated and site specific information is necessary in order to carry out a valuable analysis. In most real cases, neither all impacts of infiltration and exfiltration nor the consequences of rehabilitation techniques can be properly and exhaustively evaluated because of a lack of data, of models and of knowledge on the involved phenomena. Consequently, many hypotheses will still be introduced in the analysis, with unknown bias in the application of the methodology. Results should then always be reviewed carefully. The final decision making process should also take into account the context of the study and not forget other aspects that may not have been modelled explicitly. Additionally, the methodology, and especially the multi-criteria analysis with Electre III, facilitates the dialogue between all stakeholders and the comparison of their respective approaches and preferences. The dialogue and the decision making process itself are more important, in such a collaborative work, than the final numbers and values that would have been obtained by a single person aiming to consider all points of view.

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REFERENCES

Baer E., Le Gauffre P., Barraud S., Bertrand-Krajewski J.-L. (2005). *Proposal of a methodology to compare investment strategies accounting for infiltration / exfiltration problems and application to a semi-virtual case study*. Villeurbanne (France): INSA de Lyon, APUSS Deliverable D10, revised version July 2005, 65 p. Available at the APUSS website http://www.insa-lyon.fr/Laboratoires/URGC-HU/apuss.

Bertrand-Krajewski J.-L., Barraud S., Bardin J.-P. (2002). Uncertainties, performance indicators and decision aid applied to stormwater facilities. *Urban Water*, **4**(2), 163-179.

Delleur J.W., Reyna S., Vanegas J. (1998). Sewerage rehabilitation. in J. Marsalek *et al.* (eds.): *Hydro-informatics Tools for Planning, Design, Operation and Rehabilitation of Sewer Systems*. Dordrecht (Netherlands): Kluwer Academic Publishers, NATO ASI Series, 2. Environment, vol. 44, 415-450.

Ewan Associates, Mott Mac Donald Ltd. (2001). *Development of enhanced serviceability indicators for sewerage assets*. Reports ref.01-G003/02/Ofwat/od/dg/002/63452. Birmingham (UK): OFWAT. Available at the OFWAT website http://www.ofwat.gov.uk.

Frehmann T. (2004). *Cost-benefit analysis*. Essen (Germany): Emschergenossenschaft, APUSS Deliverable D11.2. Available at the APUSS website http://www.insa-lyon.fr/Laboratoires/URGC-HU/apuss.

Freni G., Hafskjold L.S., Montero C. (2005). *Rehabilitation technologies costs tool*. Trondheim (Norway): SINTEF, unpublished CARE-S project Report D12 "Rehabilitation Technologies Survey".

Gujer W., Larsen T.A. (1995). The implementation of biokinetics and conservation principles in ASIM. *Water Science and Technology*, **31**(2), 257-266.

Neitzke S. (2002). *Evaluation expérimentale de l'infiltration et de l'exfiltration dans les réseaux d'assainissement. Etude bibliographique et identification des sites expérimentaux*. Master thesis. Dept of Civil Engineering, INSA of Lyon, July, 105 p. + appendix (in French).

O'Brien and Gere Companies (2001). *Trenchless technologies: an economical alternative for sewer rehabilitation*. Available at the O'Brien and Gere Companies website http://www.obg.com/.

Orditz D. (2004). *Contribution à l'étude de la durabilité des réhabilitations de réseaux d'assainissement*. Paris (France): CSTB, Rapport RERAU. 52 p.

RERAU (2004). *Projet National Réhabilitation des Réseaux d'Assainissement Urbains: Restructuration des collecteurs visitables - Guide technique, tome 2*. Paris (France): Tec et Doc, mars 2004, 250 p.

Roy B. (1978). Electre III : un algorithme de classements fondé sur une représentation floue des préférences en présence de critères multiples. *Cahier du CERO*, **20**(1), 3-24.

Villanueva A., Montero C., Raclavsky J. (2004). *Rehabilitation technologies database*. Trondheim (Norway): SINTEF, unpublished CARE-S project Report D12 "Rehabilition Technologies Survey".

Vincke P. (1992). *Muticriteria Decision-Aid*. Chichester (England): John Wiley & Sons, 154 p.