FUZZY LOGIC CONTROL OF INTEGRATED WASTEWATER SYSTEMS

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Abstract: The increasing importance of environmental problems in the last decades, and the consequently stricter regulations adopted, require a holistic approach in control and operation of wastewater process, whose primary objective is to maintain a good state of the receiving waters. This paper reports the study focused on building a Fuzzy Logic Control for integrated wastewater systems. The control involves Wastewater Treatment Plants, rivers and sewers. The results obtained are encouraging: the impact in the river is reduced and the wastewater treatment improved, particularly during wet weather conditions.

Keywords: environmental engineering, fuzzy logic, integrated plant control, modelling, optimization, urban systems, waste treatment.

1. INTRODUCTION

An urban Wastewater System (WWS) is constituted of three main components: the sewer system, the wastewater treatment plant (WWTP) and the receiving waters. Most of the sewer systems are combined sewer systems: this means that they collect wastewater but can also accept rainfall runoff from the nearby drainage area (catchment). The rainfall runoff contribution results, especially during wet weather conditions, in problems both in the WWTP and in the sewer system itself. This is due to higher hydraulic loads arriving to the plant, and to the water overflowing from the designed storage basin/pipe (Combined Sewer Overflow, CSO).

With the enactment of the European Water Framework Directive (WFD, 2000/60/EC), which requires a river basin-scale approach rather than single system managements, integrated control applied to the entire system would result in the optimisation of all the involved systems.

The idea of applying Fuzzy Logic techniques to an integrated WWS is promising: the systems involved are characterized by their own variables, thresholds concentrations, processes and components descriptions. The possibility of correlating the systems to each other through simple rules and fuzzy sets appears to be the only way to easily and efficiently control an integrated system. Examples of the application of the Fuzzy Logic techniques to the wastewater field have been found in literature, but they are limited to single parts of the system. No study of the use of Fuzzy Logic to control an integrated system seems to be carried out up to now.

In this paper an integrated Fuzzy Logic Control (FLC) is presented and the obtained results are discussed and explained.

2. SYSTEM DESCRIPTION AND MODELLING

2.1 *The Wastewater System*

In Fig. 1 a schematic of the urban WWS used in this research is shown. This presents the configuration of the WWTP chosen for the research. It is an integrated anoxic–aerobic system where the removal of organic substrates and Nitrogen is obtained. Due to the external supply of Ferric-hydroxide, the abatement of the Phosphorus is also achieved. The secondary clarifier allows the settling of the particulate components, with the principal aim of obtaining a clarified effluent. The external recycle is done in order to maintain a constant concentration of biomass in the system, whereas the internal one guarantees the Nitrate presence in the first tank. The WWTP characteristics are reported in Table 1.

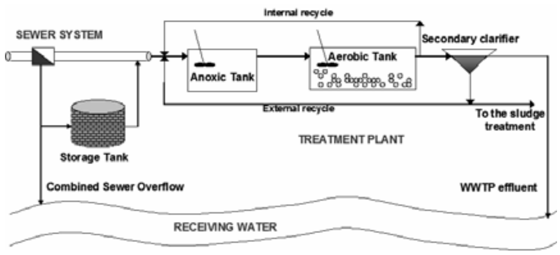

Fig. 1: The wastewater system.

A storage tank of 8000 m^3 has been inserted in the sewer in order to allow more water to be treated in the WWTP, especially during wet weather conditions. This reduces the CSOs. The sewer pipe capacity is 28725 m^3/d, equal to five times Q_F. The dry influent to the system has the component concentrations as suggested in ASM2d (IWA, 2000) and the values for the concentrations in the rainfall-runoff have been taken from the literature (Metcalf and Eddy, 1991).

Table 1: WWTP characteristics

Parameter	Description	Value
Q_F	influent flow	5745 m^3/d
Q_W	wastage flow	108 m^3/d
a	internal recycle	3
b	external recycle	1
V_1	anoxic reactor volume	1363 m^3
V_2	aerobic reactor volume	2713 m^3
A	surface of 2 clarifier	300 m^2
H	depth of 2 clarifier	3.2 m
V_s	settler volume	960 m^3
k_la	air flowrate coefficient	240 d^{-1}
$Fe(OH)_3$	$Fe(OH)_3$ dosage	12e5 g/d

2.2. *The Integrated Modelling*

The single subsystem models have been based on the state-of-the-art models in the respective fields: the ASM2d for the Activated Sludge system (IWA, 2000), the Takács model for the secondary clarifier (Takács, et al., 1991) and QUAL2E for the river (Brown and Barnwell, 1987). Interface models, based on few assumptions, have been built to connect these models. All models were implemented in Matlab/Simulink. A simplified version of a sewer system, based on the Unit Hydrograph approach, has been also modelled to simulate wet weather conditions.

Non-controlled system wet weather simulations. The system first has been run without control to assess its problems during wet weather conditions. These were needed as a starting point of the control strategies development. The rain event has been chosen with the characteristics: Rain event: B9t20, Duration: 20 min, Depth: 9 mm, Intensity: 27 mm/h, Return period: 0.1 years and starting one day after the beginning of the simulation.

The studied wastewater system is subjected to the following problems during wet weather conditions:

1. High level of Dissolved Oxygen (DO) in the anoxic tanks, due to the presence of DO in the influent as a consequence of the mixing with the rainfall runoff. This results in the inhibition of the denitrification;
2. High concentrations of Total Suspended Solids (TSS) in the effluent;
3. High concentration of total Phosphorus in the effluent;
4. Short hydraulic retention time (HRT, ratio between tank volume and flowrate) in the aerobic tank which can reduce the nitrification efficiency;
5. CSOs in the sewer.

It is important to emphasise that the concentrations of the components in the effluent have been compared with regulatory limits or quality constraints, some of which are reported in Table 2. Particularly, they are the constraints proposed in the Benchmark study (Copp, 2002) and the limits imposed by the Italian regulation and those set for the Swinstie WWTP (Glasgow, UK), which were derived by Scottish and European regulations. The abbreviations are as follows: BOD_5 =5-day Biochemical Oxygen Demand, COD = Chemical Oxygen Demand, TSS= Total Suspended Solids ,N_{AMM}= Ammonium, N_{TOT}= Total Nitrogen, P_{TOT}= Total Phosphorus

Table 2: Effluent limits constraints

Parameter (g/m^3)	**Benchmark's constraints**	**Italian regulation** (D.leg. n°152)	**Swinstie WWTP's limits**
BOD_5	10	25	20
COD	100	125	-
TSS	30	35	30
N_{AMM}	4	-	5 (3-10)-10 (11-5)
N_{TOT}	18	15	-
P_{TOT}	-	2	2

The problem related to the CSOs has not been taken into account because more than one basin is required for process optimisation and the sewer modelling and control was not an aim of this research. The attention has been focused on the WWTP and the river system. Some of the problems can be solved simultaneously:

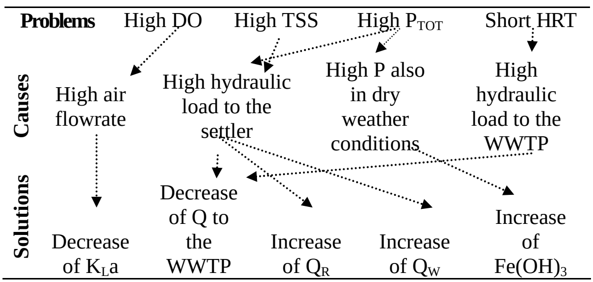

Fig. 2: Problems and solutions of the WWTP problem under wet weather conditions.

- Controlling the airflow rate will allow the reduction of the DO in both the anoxic and aerobic tank.
- Reducing the TSS in the effluent will partly reduce the total Phosphorus. In Fig. 2 the schematic of the WWTP problems and their possible solutions are reported.

3. INTEGRATED FUZZY LOGIC CONTROL

The aim is to design an integrated Fuzzy Logic Control (FLC): the WWTP control has been designed taking into account also the river conditions. The sewer has been partially involved in the control strategies, trying to deliver the maximum flow to the WWTP in order to reduce the flow to the CSO. Moreover, in the adopted solution, the actuator which decreases the flow entering the plant under critical events acts on a valve on the sewer basin.

In Fig. 4 the "trial and error" iterative approach used to design the FLC is presented. Since the WWT system is a very complex system, the same problem can be solved in different ways: the point is to find, for the specific system, the best solution. This is why an external loop is also needed. The internal loop allows the review of the FLC to optimise Membership Functions' (MF) parameters or rules. The FLC is a high-level control which defines the set-points. The FLC is integrated with P/PI controllers to allow the variables to reach the set-point.

Several solutions have been tested. Here only the final one will be reported and discussed. However, some points regarding the "trial and errors" phase are still interesting to be noted:

- The approach proposed by Tsai, *et al.* (1996), who suggested setting the return flowrate inversely proportional to the daily-variant influent flow, did not give good results if applied to flowrate variations due to rainfall events;
- In some simulations the derivative term of the variables (either of the inflow rate, or of the TSS, or of total Phosphorus) has been considered as input for the FLC, in order to anticipate the critical events and take actions to minimise its impact. However, this approach has not been resulted in any improvements in the system. This is mainly because the changes in the concentrations due the rainfall event are almost instantaneous as a consequence of the fast change in the inflow rate. This results in the fact that the rules associated with the derivative terms become active only when the impact has already taken place;
- The change in the DO set-point was also taken as the output of the FLC. The DO set-point in the aerobic tank was an input added to the FLC's variables. Similar methodologies had been used by Tong, *et al.* (1980). However this approach has shown instability in the DO concentrations.

3.1 *The proposed control strategy*

In the proposed control strategies the inputs and outputs of the FLC have been chosen as listed in Fig. 3. They are grouped together as they are associated in

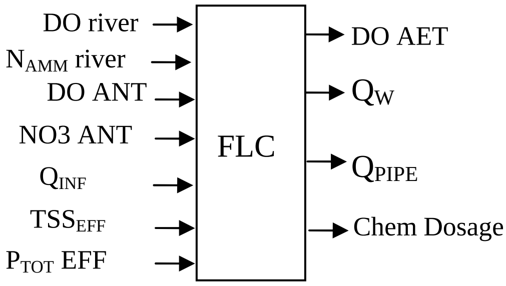

Fig. 3: Inputs and Outputs of the FLC

the rules. It is important to emphasise that Q_{PIPE} represents the maximum flowrate that can enter the plant, but this does not necessarily correspond to the flow entering the plant (it is the same only in wet weather conditions). For the first three outputs, the FLC works as a high-level control: the crisp values obtained by the FLC are the reference signals for P/PI controllers respectively in the aeration equipment (through the variation of K_La) and for the valves in the settler (wastage flowrate, Q_W) and in the basin (Q_{PIPE}). For the dosage of chemical reagent, the FLC is a low-level control, that is, its output is directly inserted in the process.

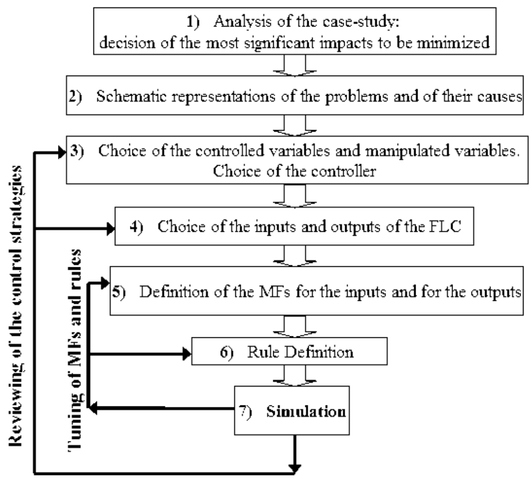

Fig. 4: The approach used in the FLC development

The control is an integrated control because two of the inputs of the FLC are the concentrations of components in the river (specifically in the WWTP's discharge point), chosen in order to take into account also the impact that the effluent has on the receiving water. Since it has been assumed that the discharge occurs in river, where the acute effects are preponderant, the variables considered have been the DO and the Ammonia: the DO depletion and high Ammonia concentrations give mostly this type of impact. If the WWTP discharge is in stagnant waters, the measure of the accumulative pollutants (e.g. total Nitrogen, total Phosphorus and heavy metals) would be more appropriate. (Schilling, *et al.*, 1997). The others inputs to the FLC have been chosen for the reasons explained as follows and in accordance with the mentioned problems of the system in wet weather conditions. The DO and Nitrate (NO_3) concentrations are measured to assess the state of the denitrification process within the anoxic tank. The influent flowrate to the WWTP (Q_{INF}) gives indications about hydraulic overloads. The TSS amount in the effluent gives evidence of problems in the settling process. Finally, the total Phosphorus is needed to know the correct dosage of chemical reagent. Regarding the outputs of the FLC, the variables have been chosen as reported in Table 4 for the following reasons:

- The necessity of controlling the DO in the aerobic tank (especially because often, in order to avoid the problem of low DO concentrations both in the aerobic tank and in the river, the airflow rate is increased, resulting in waste of money and problems in the anoxic tank);
- The need for controlling the chemical dosage (Ferric-hydroxide) on the basis of the Phosphorus concentrations in the effluent;
- The requirement of improving the settling process during hydraulic overload lperiods. This can be achieved in several ways: however the reduction of the flow entering the plant (through the control of flow leaving the basin, Q_{PIPE}) has been shown to be necessary in order to minimise the TSS effluent under the regulatory limits. In order to avoid a significant reduction of the influent, a simultaneous control of the wastage flowrate (Q_W), which is the sludge flow discharged from the bottom of the settler, has been inserted: this allows an increase of the settler downward flow which results in speeding up the settling process.

3.2 *Definition of the Membership Functions (MFs)*

This phase has involved the decision of the linguistic sets for the description of the variables, the choice of the shape of the MF for each of this set and the definitions of the parameters characterizing each MF.

Linguistic Sets. Manesis, *et al.* (1998) state that three descriptors are generally sufficient to describe the controller input variables; the outputs can be described more accurately through five descriptors. The increase in the numbers of the qualitative fuzzy regions results in an improvement of the FLC's integrity, decreasing simultaneously its granularity. However, on the other hand, the increase of the descriptors numbers results in the increase of the FLC's complexity and memory requirement, which then results in an increase of costs. Moreover, Manesis, *et al.* (1998) are doubtful whether high granularity is indeed necessary for the nature of the WWTP's processes. The approach used in this research has been the one of trying to minimise, where possible, the number of linguistic descriptors used. Particularly, four descriptors have been used only for the DO set-point in the aerobic tank, for which a more accurate definition is required, both because this output is affected by rules involving four inputs, and because small differences in the DO set-point are translated to large differences in the air flowrate requirement and then in the cost needed to maintain that concentration. Only two descriptors have been used for those variables whose values do not affect directly the system efficiency or are not indicators of it, but can reveal problems in the system: these are the DO and Nitrate concentrations in the anoxic tank, for which the linguistic variables are simply *OK* and *NotOK*. Two descriptors have been also used for the set-point of the maximum flow leaving the basin (*Normal*, *High*), mainly because just the diversification between wet weather conditions (resulting in high TSS leaving the settler) and dry weather conditions was needed. For all the other variables, three descriptors have been used. Triangular and trapezoidal MFs have been used.

Definition of the parameter characterizing each MF. This is probably the most delicate step. For the river, the quality criterion suggested by Schilling, *et al.* (1997) and reported in Table 3 has been used. These values, which refer to small rivers, are extreme value statistics: for example, in order to avoid being rated having a bad status, the Ammonia concentrations can not be higher than 0.4 mg/l, during one our, more often than once per year.

Table 3: Small river water quality criteria (duration 1h, return period 1h)

Parameter	**Values for of ecological quality**			
	good	sufficient	insufficient	bad
DO (mg/l)	4	3	2	1
NH_3 (mg/l)	0.1	0.2	0.3	0.4

The limits imposed for the Ammonia seem to be too restrictive, especially for the conditions of the river studied whose concentrations are already around 0.2 mg/l before the rainfall event at the discharge point: they can be reached only through an increase of the DO supply which results in significant increase of costs. Two alternatives will be then analysed: the one which respects the limits imposed in Table 5 requires higher DO. In both cases, however, the Ammonia in the effluent is significantly under the regulatory limits.

Regarding the WWTP variables, the values used have been the WWTP effluent limit concentrations, as they are reported in Table 3. The part of variables space representing the normal conditions has been parameterised through the concentrations of the variables in the dry weather/steady-state conditions.

3.3 *The Fuzzy Inference System (FIS) and the Rules*

The Mandani's fuzzy inference method has been used supported by the minimum method for the AND operator, the maximum method for the OR operator, the minimum method for the implication step, the centroid method for the defuzzification.

Twenty-two rules were developed. They were divided into three groups: those aimed to minimise the TSS effluent and affecting Q_W and Q_{PIPE}, those for the minimisation of the total Phosphorus in the effluent and those for the DO control. The last case is where the two alternatives have been proposed, which differ just for two rules definitions:

Case A: Notwithstanding that the Ammonia concentration in the effluent is under the regulations limits, its impact in the river is high. However, the

DO concentration in the aerobic tank is very low and this results in low cost;

<u>Case B</u>: The Ammonia concentration in the river is lower, but higher air flowrates are required to reach this scope.

In Fig. 5 it is possible to see the difference of the Oxygen requirement for Case A and Case B.

It is important to point out that in the development of the rules, the river-part rules and MFs have been mostly written/designed on the basis of general conditions and not specific for the system, with the aim to have rules which can be applied in every river system. The WWTP’s FLC part can still be applied in most of the cases, but a specification of the control has been needed since the WWTPs can vary significantly in capacity and configurations, and therefore the particular case studied has to be taken into consideration.

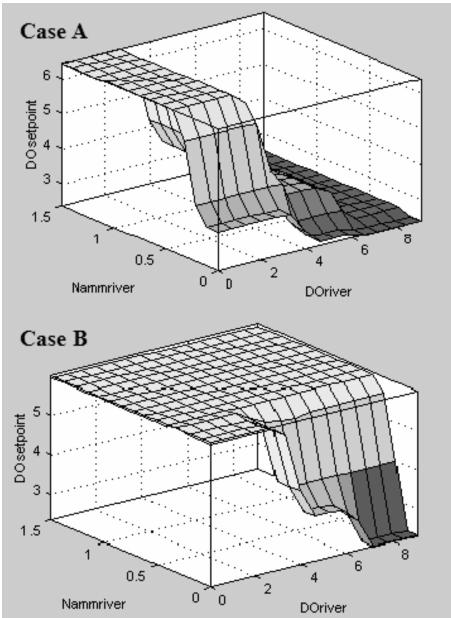

Fig. 5: Case A and Case B: DO set-point as a function of N_{AMM} and DO in the river.

4. RESULTS AND DISCUSSION

Only the main results are presented here.

4.1 The controlled air flowrate

In Fig. 6 the air flowrate coefficient is reported for the three cases studied, which are the non-controlled system, case A and case B. There is a significant reduction in the air flowrate required in the aerobic tank when the DO control is applied. Improvements are evident for both the controlled cases. However, in case B the air flowrate needed to reach the desired conditions (lower Ammonia impact in the river) are higher than in case A. In steady-state conditions the air flowrate coefficient is equal in both the controlled cases. The reduction of the required air flowrate results in a decrease of the operational costs.

4.2 *Results of the control in the sewer system*

The WWTP’s influent reduction has been necessary to decrease the TSS in the effluent. This is the case where the control introduction has side effects: in this case the minimisation of the TSS is felt downstream to the AS system (in the sludge treatment part, through the increase of Q_W) and upstream. The reduction of the flowrate entering the plant results obviously in the increase of the overflow from the basin. However, Fig. 7 shows that the increase of the CSO due to the control is very small and simultaneously the basin volume is better exploited. The impact on the river of the CSO in terms of pollutants is also slightly different for the non-controlled and controlled cases.

4.3 *Results of the control in the WWTP*

<u>The WWTP effluent</u>. The efficiency of the control inserted has to be assessed principally in the effluent quality, compared with the limits in Table 3. The results obtained for the TSS and Total Phosphorus are reported in Fig.s 8 and 9. Besides the reduction of all the component concentrations, the control is able to reduce the TSS and the total Phosphorus under the imposed limits: this was an aim of the control which is then effectively achieved.

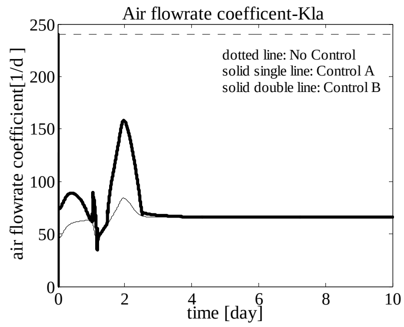

Fig. 6: The controlled air flowrate

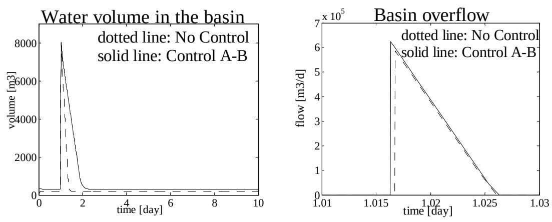

Fig. 7: The water volume in the basin and the CSO

<u>The Anoxic Tank</u>. Another target of the FLC was to guarantee the anoxic condition also during wet weather conditions. Fig. 10 shows that the anoxic conditions are maintained during almost all the simulation time (in IWA, 2000, the concentration of DO which limits the denitrification is 0.2 g/m^3). In case A lower concentrations are present. In case B the DO concentration reaches higher values as a consequence of the higher DO set-point in the aerobic tank. Notwithstanding the conditions in case A are preferable, the DO concentration in case B is still acceptable.

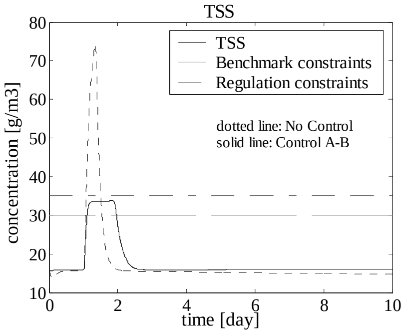

Fig. 8: Total Suspended Solids in the effluent

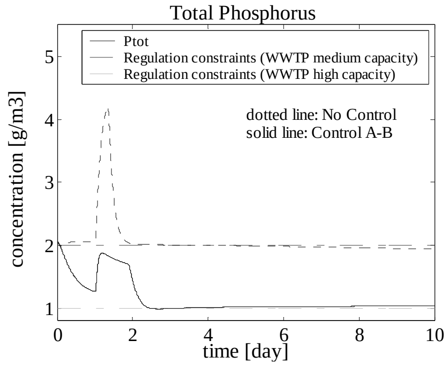

Fig. 9: Total Phosphorus in the effluent

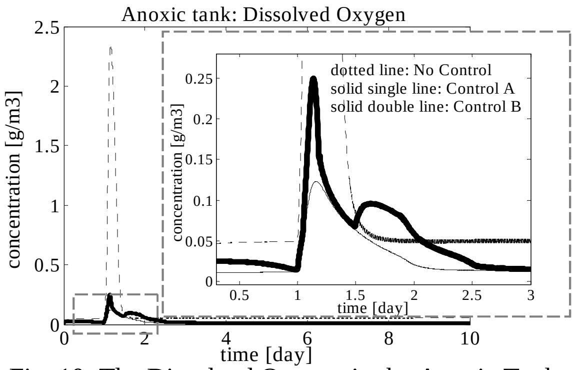

Fig. 10: The Dissolved Oxygen in the Anoxic Tank

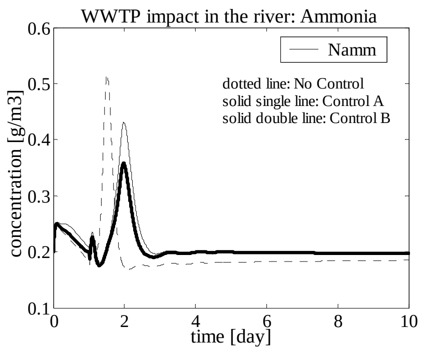

Fig. 11: Ammonia concentration in the river

4.4 *Results of the control in the river*

The attention is focused on the Ammonia and DO behaviours, since they are inputs of the FLC. The DO concentrations in the controlled system are lower than those in the non-controlled system, but still very good (concentrations higher than 7 mg/l). In Fig. 11 the Ammonia concentrations is reported. Due to the FLC, the Ammonia concentration in the river, during wet weather conditions, decreases. The less impacting situation is the case B, which however require higher operational cost for DO supply.

5. CONCLUSIONS

The results show that the FLC introduction allows minimising the WWTP impact and, it does not result in a high side effect upstream in the sewer system. This study has proved that the FLC can be efficiently applied to an IWS. The only difficulty which has arisen is in the reduction of the Ammonia concentration in the river under the "standard" quality concentrations. Obviously when two different systems are integrated, some compromises have to be reached: for the specific systems the river water quality objective is conflicting with the aim of reducing the treatment costs. However, the FLC seems to give a better solution for these cases.

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