Planning regional wastewater systems across borders

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ABSTRACT

Regional wastewater systems are aimed at guaranteeing surface water quality by properly collecting and treating the wastewater generated in the population centres of a region. But the most suitable planning regions are often divided by political or social boundaries and may include upstream-downstream surface water quality conflicts. A cross-border planning approach allows the coordination of pollution control and can embrace both economic and environmental considerations. In this paper, an optimization model for regional wastewater system planning across borders is presented to identify reference solutions for negotiation between parties, for the layout of the infrastructure to be included in the system. The model takes into account costs and the water quality in the receiving body, and is therefore able to meet the surface water quality standards in the shared waterway. The model is solved through a heuristic method based on a simulated annealing algorithm enhanced with a local improvement procedure. A region designed to replicate a real-world problem containing two countries is used as a case study. The transboundary wastewater system planning approach is compared with the consideration of separate systems for each country. The features of the transboundary solutions are discussed, with particular focus on the basis of the asymmetries in the willingness to pay. Two possibilities for cost allocation are analysed.

KEY WORDS: *Transboundary wastewater management, optimization, simulated annealing, willingness to pay.*

INTRODUCTION

Sanitation is generally considered to be the primary reason for the vast worldwide increase in life expectancy during the last century (Ferriman, 2007). The need to preserve the good quality of water bodies to protect human health and the environment has led to the definition of several environmental guidelines and regulations to restrict pollutant discharges. The pollution problems faced by water bodies such as rivers are extremely relevant in regions with dense urban developments. Regional wastewater systems are aimed at guaranteeing surface water quality by properly collecting and treating the wastewater generated in the population centres of a region.

A regional wastewater system solution comprises the layout of the sewer network (including possible pumping stations) that will connect the population centres with the river, and the location, type and size of wastewater treatment plants (WWTPs) where the wastewater will be treated before being discharged into the river. Because of the large, irreversible investment involved, and because of the very large number of possible configurations, the search for the best regional wastewater system should be pursued through optimization models. Melo and Camara (1994) presented a survey of the first optimization models applied. More recently, Cunha *et al.* (2009) described a more realistic discrete nonlinear optimization model for regional wastewater system planning. A model of this type enables solutions to be evaluated for the cost of installing, operating and maintaining the infrastructure, and for water quality in the river that receives the treated wastewater generated in the region. Water quality can be assessed using various environmental parameters, and it varies in accordance with the characteristics of the river and the effluent discharged into it.

The basin scale is usually considered to be the natural unit for managing water resources. In wastewater system planning, approaches at such regional level take advantage of scale economies, while achieving a better environmental performance. But both river basins and other appropriate regions for the planning approach are often divided by political or social boundaries. The multiplicity of parties involved may include conflicting ancient rivalries or different development goals. Such unfavourable political framework conditions would benefit from a planning approach across borders to help in the integrated decision-making process. The transboundary Rhine river protection program was one of the earliest well-documented success stories of international river cooperation (Mostert, 2009). In more asymmetrical settings situations such as in the US/Mexico environmental relations, Fischhendler (2007) focused on the pollution abatement regime along the border cities of Tijuana and San Diego. In situations of asymmetries such as this, the well-known “polluter pays” principle can be quite inappropriate, and the willingness to pay question arises. Therefore, alternative cost allocation principles become more suitable (Schalimtzeka & Fischhendler, 2009).

In this paper, we present an optimization model suitable for regional wastewater system planning acros borders. The model aims to find reference solutions for negotiation between parties, taking into account costs and the surface water quality in the shared-waterway. The model can be used as a decision-aid tool in the often problematic geopolitical settings. Different institutional options are considered, depending on whether decisions are taken and solutions implemented unilaterally, for each country separately, or through an integrated transboundary wastewater system approach. The establishment of an international water regime through the transboundary approach should provide the coordination of pollution control, thereby handling situations with upstream-downstream conflicts over wastewater treatment efficiencies and water quality standards. In joint management of this type, the way the cost is shared by each country poses an additional question. Two different principles related to willingness to pay are analysed: the cooperation principle; and the beneficiary principle.

We next present the proposed optimization model and its solution method, based on a hybrid algorithm. Second, we present a case study on transboundary wastewater system planning. The results for a separate system solution and an international solution are compared. Based on the results, the features of the transboundary planning are discussed, in particular relating to the cost allocation possibilities. We conclude with a comment on the outlook for future work.

METHODS

Optimization Model

The proposed model is based on the regional wastewater system planning model described in Cunha *et al.* (2009). The objective function consists of minimizing the cost of the regional wastewater system and is subject to different constraints to ensure that the sewer network will be designed according to hydraulic laws and regulations. The water quality of the river is evaluated according to the dissolved oxygen (DO) concentration.

The formulation of the model is as follows:

$$\text{Min} \quad C \tag{1}$$

subject to:

$$\sum_{j\in \boldsymbol{N_S}\cup\boldsymbol{N_I}} Q_{ji} - \sum_{j\in\boldsymbol{N}} Q_{ij} = -QR_i, \quad i\in\boldsymbol{N_S} \tag{2}$$

$$\sum_{j\in \boldsymbol{N_S}\cup\boldsymbol{N_I}} Q_{jl} - \sum_{j\in\boldsymbol{N}} Q_{lj} = 0, \quad l\in\boldsymbol{N_I} \tag{3}$$

$$\sum_{j\in \boldsymbol{N_S}\cup\boldsymbol{N_I}} Q_{jk} = QT_k, \quad k\in\boldsymbol{N_T} \tag{4}$$

$$\sum_{i\in\boldsymbol{N_S}} QR_i = \sum_{k\in\boldsymbol{N_T}} QT_k \tag{5}$$

$$\sum_{p\in\boldsymbol{T}} y_{kp} \le 1, \quad k\in\boldsymbol{N_T} \tag{6}$$

$$QT_k \le \sum_{p\in\boldsymbol{T}} QT\max_{kp}\, y_{kp}, \quad k\in\boldsymbol{N_T} \tag{7}$$

$$Q\min_{ij}\, x_{ij} \le Q_{ij} \le Q\max_{ij}\, x_{ij}, \quad i\in\boldsymbol{N_S}\cup\boldsymbol{N_I}\,;\, j\in\boldsymbol{N} \tag{8}$$

$$DO_k \ge DO\text{min}, \quad k\in\boldsymbol{N_T} \tag{9}$$

$$x_{ij}\in\{0,1\}, \quad i\in\boldsymbol{N_S}\cup\boldsymbol{N_I}\,;\, j\in\boldsymbol{N} \tag{10}$$

$$y_{kp}\in\{0,1\}, \quad k\in\boldsymbol{N_T}\,;\, p\in\boldsymbol{T} \tag{11}$$

$$QT_k \ge 0, \quad k\in\boldsymbol{N_T} \tag{12}$$

$$Q_{ij} \ge 0, \quad i\in\boldsymbol{N_S}\cup\boldsymbol{N_I}\,;\, j\in\boldsymbol{N} \tag{13}$$

where: $\boldsymbol{N_S}$ is a set of wastewater sources; $\boldsymbol{N_I}$ is a set of possible intermediate nodes; $\boldsymbol{N_T}$ is a set of possible WWTPs and related river reaches; $\boldsymbol{N}$ is a set of nodes ($\boldsymbol{N_S} \cup \boldsymbol{N_I} \cup \boldsymbol{N_T}$); $\boldsymbol{T}$ is set of WWTP types (primary and secondary treatment); C is the cost of the solution to be implemented; Q_{ij} is the flow carried from node i to node j; QR_i is the amount of wastewater produced at node i; QT_k is the amount of wastewater conveyed to a WWTP located at node k; $QTmax_{kp}$ is the maximum amount of wastewater that can be treated in a WWTP of type p at node k; $Qmin_{ij}$ and $Qmax_{ij}$ are respectively the minimum and maximum flows allowed in the sewer linking node i to node j; DO_k is the lowest DO concentration in river reach k, in the solution to be implemented; DO_{min} is the minimum DO concentration defined by water quality standards; x_{ij} is the binary variable that takes the value one if there is a sewer to carry wastewater from node i to node j, and is zero otherwise; y_{kp} is a binary variable that takes the value one if there is a WWTP of type p at node k, and is zero otherwise.

The objective function (1) expresses the minimization of the total discounted costs for installing, operating, and maintaining sewer networks and WWTPs. The sewer network costs depend on the wastewater flow (thus, on the diameter of commercially available sewer pipes), on the length of sewers, and on the hydraulic heads at the ends of sewers. They include the cost of installing, operating, and maintaining the pump stations needed to lift wastewater from low-head to high-head points. The WWTPs' costs depend on the amount and type of wastewater treatment that they handle. Larger WWTPs are more expensive but benefit from scale economies. The greater treatment efficiencies are also more expensive. In particular, the costs of secondary WWTPs are considered to be double those of primary WWTPs.

Constraints (2), (3), and (4) are continuity equations to ensure that all nodes, as well as the whole system in general, are in equilibrium with respect to wastewater flows. Constraint (5) ensures that all the wastewater generated in the region will be treated at one WWTP or another. Constraint (6) guarantees that there will be at most one WWTP, of a specific type, in each treatment node. Constraint (7) ensures that the wastewater sent to any WWTP will not exceed given maximum values. Constraint (8) ensures that the flow carried by sewers will be within given minimum and maximum values. These values depend on the diameter and slope of sewers, and on flow velocity requirements. Constraint (9) is an environmental constraint to ensure that the lowest DO concentration along a river reach is higher than the standard DO concentration defined for that reach. Constraints (10) to (13) specify the domain of the decision variables.

Solution method

To represent the problems as accurately as possible, the optimization model incorporates discrete variables and nonlinear functions. Even for small-size examples, such models can be extremely difficult to solve. In general, they must be handled through heuristic algorithms. A heuristic method based on a hybrid algorithm composed of a simulated annealing (SA) algorithm complemented by a local improvement (LI) procedure is used. An SA is an algorithm that reproduces the annealing process in metallurgy (Kirkpatrick, 1983). The SA algorithm starts with an initial feasible solution and randomly changes it to new candidate solutions until arriving at a near-optimal solution. The transition between solutions is regulated according to a cooling schedule. The LI procedure starts with the best solution identified through the SA algorithm and moves into the best solution within all possible solutions its neighbourhood. The implementation and development of an efficient hybrid algorithm of this type is explained in Zeferino *et al*. (2009).

For each candidate solution, a hydraulic simulation model is used to design sewers, WWTPs, and possible pump stations complying with all relevant regulations. In addition, a water quality simulation model is used to estimate the effects of effluent discharges in the river.

CASE STUDY

The case study used to illustrate the potential of the proposed model is based on a theoretical region, covering two countries: Country A and Country B. Country A is on the left, with an area of 550 km^2 and a total population of 80 thousand inhabitants. Country B is on the right, with an area of 700 km^2 and a total population of 70 thousand inhabitants. Figure 1 shows the topography of the international region covering the two countries. The maximum height of the region is 200 m. The bottom of the region is bordered by a transboundary river that flows from left to right. The total area of the international region is 1250 km^2, corresponding to 50 km along the river and 25 km in the orthogonal direction. Figure 2 presents the spatial distribution of the populations (figures close to population centres indicate population in thousands), the intermediate nodes (needed for the appropriate representation of topography and/or the early regrouping of sewers), and the possible locations for national or international WWTPs.

The countries share a river that runs for 50 km through the region and flows from Country A to Country B. However, the water quality standards defined for surface waters vary according to the country. In this case study, it is considered that Country B is wealthier than Country A and is thus willing and able to spend more on higher water quality standards. Country A has a DO standard of 5.0 mg/L whereas Country B has a DO standard of 6.5 mg/L. Since Country B is located downstream of the border, it relies on the water quality provided upstream through Country A.

Because of the different economic strength and water quality standards defined for each country, the type of WWTPs that they are willing to install is not the same. Country A is able to install primary WWTPs, with pollutant removal efficiencies around 25%. Country B attempts to fulfil its water quality standards by installing secondary WWTPs, with pollutant removal efficiencies around 90%.

Two institutional options are considered for the solutions of the regional wastewater system that can be used for negotiation between countries. They depend whether there is a transboundary wastewater planning with coordination of pollution control or not:

- **1 – Separate system for each country**: the first option consists of designing independent wastewater systems for Country A and Country B. Each system is designed with a cost minimization objective. The systems aim at guaranteeing, if possible, the water quality in the river where the effluent is discharged, according to the standards defined by the respective country.

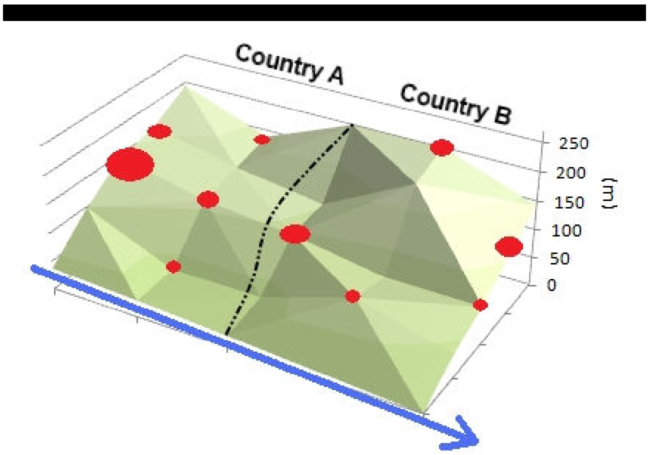

Figure 1. Topography of the case study region

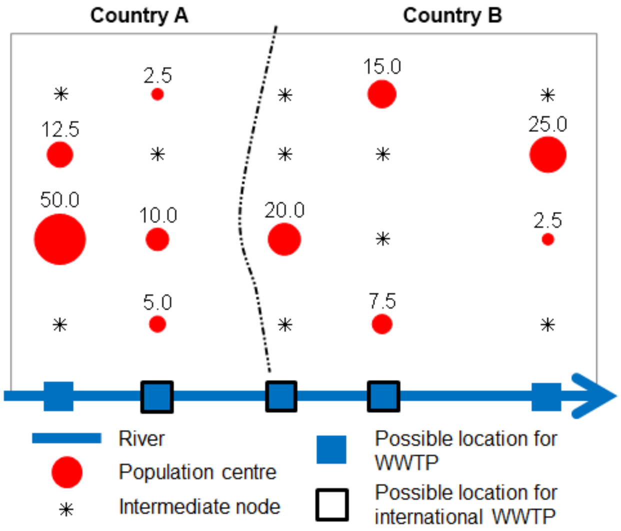

Figure 2. Spatial distribution of population (in thousands) and possible location for WWTPs

- **2 – International system for the region**: the second option considered consists of designing a transboundary wastewater system for the entire region. In particular, international WWTPs are allowed to be constructed close to the boundary, in both countries. Planning at international level enables coordination of pollution control and might provide better environmental solutions, while taking advantage of scale economies. But the country with fewer economic resources might not be interested in paying the additional cost of better WWTPs, and thus the willingness to pay question arises.

RESULTS

The wastewater system for the case study region was solved both for separate systems for each country or for a single international wastewater system for the entire region. An SA algorithm enhanced with an LI procedure was used to solve the optimization model. The results are presented below.

Table 1. *Cost of* separate *solutions for each country*

Country	***Solution costs (M€)***			
	Sewers	*Pump stations*	*WWTP*	*Total*
Country A	5.57	0.11	6.01	11.69
Country B	10.14	0.00	9.48	19.62

Separate system for each country

The configuration of the solutions obtained when the wastewater system is designed independently for each country is shown in Figure 3. The respective costs are presented in Table 1. This is the minimum price that each country would pay to collect and treat their wastewater. The cost of Country A's wastewater system (11.69 M€), is about 40% lower than the cost determined for Country B (19.62 M€). This is because, although Country A has a slightly larger population and requires one pump station, its region has a smaller area and thus a shorter length of sewers (hence lower cost of sewers), but the main difference lies in the wastewater treatment. Country A uses only primary WWTPs, whereas Country B makes use of the more costly secondary WWTPs.

The effort from Country B to preserve water quality through the secondary WWTP is conditioned by the inevitable effects derived from the upstream discharges by Country A. Figure 4 shows the DO concentrations along the transboundary river. In the reaches contained in Country A, the lowest DO concentrations are always higher than the DO standard defined there (5.0 mg/L). The river enters Country B with a DO of 5.2 mg/L, which is already lower than the water quality standard defined for Country B. Therefore, for any solution obtained for the wastewater system of Country B, its DO standard (6.5 mg/L) can never be guaranteed. The minimum cost solution obtained for this country has a single effluent discharge in the secondary WWTP installed at the node further downstream, but the water quality standards are always violated for the first 15.5 km of the country.

International system for the region

The establishment of an international water regime allows the coordination of pollution control and possible cost savings. The solution obtained for the case study when the wastewater system is designed at transboundary level is shown in Figure 5. In this solution, all the wastewater generated in Country A, together with some discharges of Country B, is treated in a single international WWTP for secondary treatment. Figure 6 shows the DO concentrations along the reaches of the transboundary river. In this solution, not only is the DO standard in Country A (largely) guaranteed, but the 6.5 mg/L DO standard for Country B is achieved, too. Therefore, the environmental advantages of this transboundary system are considerable.

The cost breakdown for the international system solution is shown in Table 2. Regarding these costs, the transboundary design allows advantage to be taken of scale economies, related particularly to the larger WWTP. However, the total cost (36.31 M€) of the system is higher than the sum of the costs of the two separate solutions for each country. This is only because of the cheaper primary WWTPs of Country A in the separate systems solution, otherwise the international system costs would be lower.

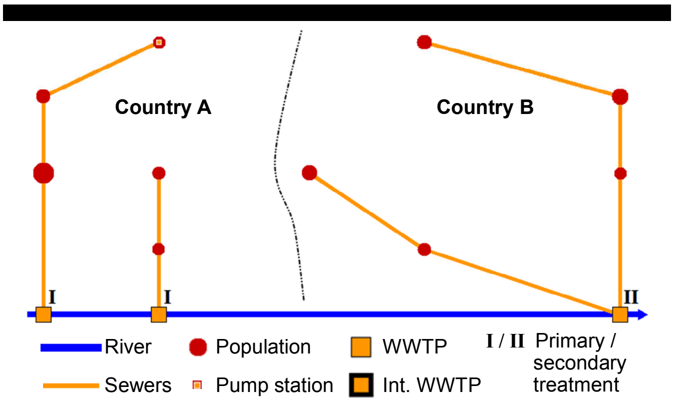

Figure 3. Configuration of the separate solutions for each country

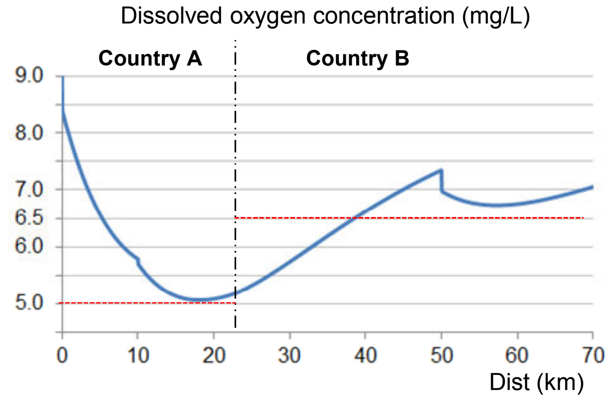

Figure 4. Dissolved oxygen throughout the river

In a solution of this type, a very important issue is determining a fair cost allocation. Two types of cost allocation principles have been analysed in this paper.

Cooperation principle:

The most intuitive situation would be for each country to pay its share for wastewater collection and treatment. The international system solution costs (Table 2) allocated to each country in this manner is shown in Table 3. Compared with the costs of the separate solutions (Table 1), Country A pays about 63% more. This is because longer sewers are required to transport the wastewater to the international WWTP, and also because of the upgrading from primary WWTPs to a secondary WWTP in the transboundary system. The costs of this international WWTP are split according to the amount of wastewater from each country. Country B will pay about 11% less than in the separate solution, mostly because of the savings provided by scale economies in the larger international WWTP.

It might not be suitable to allocate such high cost increase to Country A just to provide DO standards that are set by Country B. Since Country B is the one that most benefits from the international secondary WWTP, we come to the proposal of an alternative cost allocation.

Beneficiary principle:

A plausible situation for cost allocation is that Country B should pay the difference for the improved solution. This is because Country B is the wealthier country with stricter water quality standards and most benefiting from the

Table 2. *Cost of international solution*

Country	***Solution costs (M€)***			
	Sewers	*Pump stations*	*WWTP*	*Total*
Total	17.26	0.11	19.23	36.31

Table 3. Cost of international solution by country – cooperation principle

Country	***Solution costs (M€)***			
	Sewers	*Pump stations*	*WWTP*	*Total*
Country A	8.74	0.11	10.26	19.11
Country B	8.52	0.00	8.98	17.49

Table 4. Cost of international solution by country – beneficiary principle

Country	***Solution costs (M€)***			
	Sewers	*Pump stations*	*WWTP*	*Total*
Country A	5.57	0.11	6.01	11.69
Country B	11.70	0.00	13.22	24.92

international system. The difference to pay is the difference between the total cost of the international system (Table 2) and the cost that Country A would pay anyway if it opted for the separate solution (Table 1). These costs are shown in Table 4. In this solution, Country B has to pay 24.92 M€, making a difference of 5.30 M€, that is, about 27% more than its separate solution would be. This cost increase corresponds to the amount required to guarantee their DO standards.

CONCLUSION

This study has presented an optimization model suitable for regional wastewater system planning across borders. The transboundary approach offers the coordination of pollution control, handling situations with upstream-downstream water conflicts. The proposed model aims at bringing better insight into decision-making, by explicitly taking into account economic concerns about the cost of the infrastructure and environmental concerns in terms of surface water quality of the shared waterway.

The results show that the transboundary solution affords considerable environmental advantages, in particular by guaranteeing different water quality standards. The transboundary approach is important in a perspective that the environment is global, borderless and convenient for everyone, and is especially suited in a setting where there is no external regulatory authority. The way the cost is shared between the different parties involved was addressed according to the asymmetrical willingness to pay. Two extreme situations of cost allocation were analysed. A soft version of these could be adopted depending on agreement between negotiating parties, in particular on the willingness to pay and environmental awareness of the country in position of economic, political and power superiority.

There are several directions for future work. Cost allocation is a key question that needs to be explored. Further work will consider different cost allocation measures and take into account new cost constraints and other economic issues. Future work will also include different treatment efficiencies, handled as a decision variable in the optimization model. Different water quality parameters can be studied, too. Finally, the application to a real world case study will shed new light on the advantages of this type of approach.

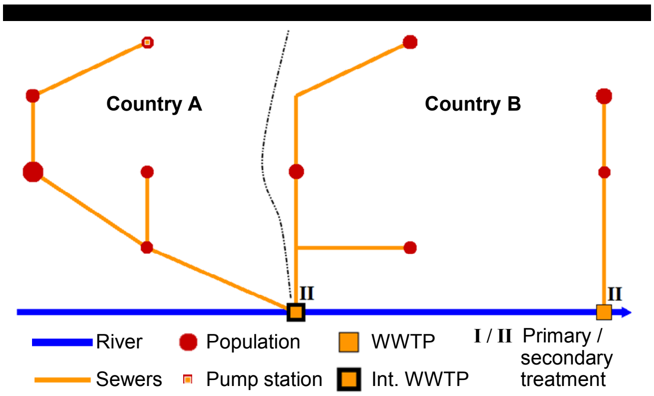

Figure 5. Configuration of the international solution

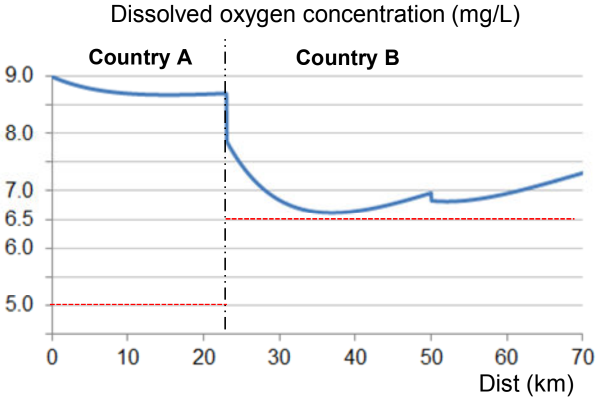

Figure 6. Dissolved oxygen throughout the river

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