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PLANNING REGIONAL WASTEWATER SYSTEMS ACROSS BORDERS

J.A. ZEFERINO[1], M.C. CUNHA[1], A.P. ANTUNES[1]

1 - Dept. of Civil Engineering, Univ. of Coimbra, Polo II, 3030-788, Coimbra, Portugal

Abstract:

Regional wastewater systems are aimed at guaranteeing surface water quality by properly collecting and treating the wastewater generated in the population centers 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 for the coordination of pollution control and can embrace both economic and environmental considerations. In this paper, a methodology for wastewater system planning across borders is presented. An optimization model is used to identify reference solutions for negotiation between parties, regarding the layout of the infrastructure to be included in the system. The model takes into account costs and water quality in the receiving water body, and is therefore able to meet surface water quality standards in the shared waterway. A heuristic method is used to solve the model, 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 willingness to pay and different cost allocations.

Keywords: Transboundary wastewater management, optimization, simulated annealing, willingness to pay, cost allocation.

1. INTRODUCTION

Sanitation is generally considered to be the primary reason for the vast worldwide increase in life expectancy during the last century [1]. 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 centers of a region.

A regional wastewater system solution comprises the layout of the sewer network (including possible pumping stations) that will connect the population centers 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 and upfront 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 [2] presented a survey of the first optimization models applied. When all the relevant features of these problems are taken into account, the subsequent models can be extremely difficult to solve. Modern heuristics are often inspired in natural processes to apply search strategies that can avoid local optima and have become very popular among scientists and engineers to handle such models [3]. In particular, the simulated annealing (SA) algorithm has been used with remarkable results in several hydraulic system planning models [4], [5]. Recently, Cunha et al. [6] described a realistic discrete nonlinear optimization model for regional wastewater system planning solved through an SA algorithm. A model of this type enables solutions to be evaluated against the cost of installing, operating and maintaining the infrastructure, and against the 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. An optimal solution would be the one that yields a minimum cost for collecting and treating the wastewater generated in the region while ensuring the water quality in the river.

In water resources the basin scale is usually considered to be the natural unit for the management approaches. Similar regional level approaches to wastewater system planning can take advantage of scale economies, while achieving a better environmental performance. But both river basins and other appropriate regions for the planning are often divided by political or social boundaries. The multiplicity of parties involved may include conflicting ancient rivalries or different development goals. Such unfavorable political framework conditions would benefit from a planning approach across borders to help in the integrated decision-making process, allowing the coordination of pollution control. The transboundary Rhine river protection program in Europe was one of the earliest well-documented success stories of international river cooperation as described in Mostert [7]. The agreement between riparian nations comprises issues such as water needs, water quality standards and wastewater treatment costs. The Polluter Pays Principle (PPP) is often presented as an equitable and fair way for appropriating the cost of pollution abatement. The PPP is assumed to provide economic efficiency and environmental sustainability but has been found difficult to implement, leading to the proposal of alternative cost allocation principles [8]. The willingness to pay problem particularly arises in asymmetrical situations, such as in the USA/Mexico environmental relations. Fischhendler [9] focused on the pollution abatement regime along the border cities of Tijuana and San Diego. One of the proposed alternative cost allocations addressing such situations of asymmetries is the Beneficiary Pays the Difference Principle (BPDP) that overcomes questions of justice by making each polluter pay only for bringing wastewater to a level compliant with its own standards [8]. To achieve the pollution abatement targets different economic incentive instruments can be used, such as emissions taxes and pollution abatement subsidies. These targets can be attained at minimum cost through economically efficient methods as the facilitation of bargaining, however subjected to some limitations [10].

Optimization based approaches have been applied in recent years to different transboundary water resources problems to find cost-efficient optimal solutions. Devi et al. [11] presented a linear programming optimization model formulation for the analysis of a transboundary problem of water allocations in a large river basin system. In groundwater management a response matrix minimization was used by Psilovikos [12] to a transboundary aquifer problem. Teasley and McKinney [13] applied a nonlinear multiobjective model for the allocation of water and energy resources, considering transboundary cooperation and benefits sharing. In wastewater systems planning problems, transboundary approaches are yet to be implemented, in particular embracing instruments for pollution control in the shared rivers. In such non-uniform mixing environments it is difficult to identify the magnitude of the damage which results from a given quantity of emissions making the planning of pollution control measures even more challenging.

In this paper, we present a methodology for planning wastewater system across borders. An optimization model is used to identify reference solutions for negotiation between parties, taking into account costs and the resulting surface water quality in the shared-waterway. The model can be used as a decision-aid tool in the often problematic geopolitical settings. Different management options are considered, depending on whether decisions are taken and solutions implemented unilaterally, for each country separately without coordination, or through an integrated transboundary wastewater system approach. A transboundary approach allows for the coordination of pollution control, either through separate systems or by establishing an international water regime. This should handle situations with upstream-downstream conflicts over wastewater treatment efficiencies and water quality standards. In joint management of this type, the willingness to pay of each country poses an additional question, and different principles related to the way costs are shared can be applied.

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. A comparison is made between the results obtained for separate system solutions, with and without pollution coordination, and an international solution. Based on these results, the features of the transboundary planning are discussed, in particular regarding the cost allocation possibilities. We conclude with a comment on the outlook for future work.

2. METHODS

2.1. OPTIMIZATION MODEL

The proposed model is based on the regional wastewater system planning model described in Cunha et al. [6]. 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 comply with all relevant regulations. The water quality of the river is evaluated according to the dissolved oxygen (DO) concentration. This is one of the most crucial parameters of water quality, because many forms of life in water bodies can only survive in the presence of minimum levels of oxygen. The same concepts could also be applied to the management of other types or combinations of pollutants.

The formulation of the annualized model is as follows:

$$\text{Min} \sum_{R} \left(\sum_{i \in N_S \cup N_I} \sum_{j \in N} C_{ijr}\left(Q_{ij}, L_{ij}, E_{ij}, x_{ij}\right) + \sum_{k \in N_T} \sum_{p \in T} C_{kpr}\left(QT_k, y_{kp}\right) \right) \quad (1)$$

subject to:

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

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

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

$$\sum_{i \in \boldsymbol{N_S}} QR_i = \sum_{k \in \boldsymbol{N_T}} QT_k \quad (5)$$

$$\sum_{p \in \boldsymbol{T}} y_{kp} \leq 1, \quad k \in \boldsymbol{N_T} \quad (6)$$

$$QT_k \leq \sum_{p \in \boldsymbol{T}} QT\max_{kp} \, y_{kp}, \quad k \in \boldsymbol{N_T} \quad (7)$$

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

$$DO_k \geq DO\min_r, \quad k \in \boldsymbol{N_T} \, ; r \in \boldsymbol{R} \quad (9)$$

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

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

$$QT_k \geq 0, \quad k \in \boldsymbol{N_T} \quad (12)$$

$$Q_{ij} \geq 0, \quad i \in \boldsymbol{N_S} \cup \boldsymbol{N_I} \, ; j \in \boldsymbol{N} \quad (13)$$

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); $\boldsymbol{R}$ is a set of countries; C_{ijr} is the discounted costs, at country r, for installing, operating, and maintaining a sewer linking node i to node j and a possible pump station to elevate wastewater from node i to node j; C_{kpr} is the discounted costs for installing, operating and maintaining a treatment plant of type p at node k of country

r; Q_{ij} is the flow carried from node i to node j; QR_i is the amount of wastewater produced at node i; L_{ij} is the length of the sewer linking node i to node j; E_{ij} is the difference of hydraulic heads between node i and node j; 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; $DOmin_r$ is the minimum DO concentration defined by water quality standards in country r; 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 the systems of each country, or for both systems simultaneously. These costs include installing, operating, and maintaining sewer networks and WWTPs, considering a time discount rate of 4% over a 20-year time horizon. The sewer network includes the cost of sewers and pump stations. The cost of sewers depends on the wastewater flow (thus, on the diameter of commercially available sewer pipes) and on the length of the sewers. It includes the costs for excavation, assembly and labor. The cost of pump stations depends in addition on the hydraulic heads at the ends of sewers, and includes the electro-mechanical equipment and the energy cost. The cost of WWTPs depends 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 [14].

Constraints (2), (3), and (4) are continuity equations to ensure that all nodes are in equilibrium with respect to wastewater flows. Constraint (2) applies to population center nodes, where there is an inflow of wastewater into the sewer network, constraint (3) applies to intermediate nodes, and constraint (4) applies to WWTPs nodes, where there is an outflow of wastewater from the sewer network. 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 the respective country. Constraints (10) to (13) specify the domain of the decision variables.

2.2. 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 [15]. An SA algorithm starts with some initial (feasible) current solution, and progressively searches for a good-quality solution (a low-cost solution in a cost-minimization problem). In each iteration of the SA algorithm, a change of solution is produced, chosen at random in the neighborhood of the current solution. The transition between solutions is regulated by a parameter called temperature, according to a cooling schedule. Initially, at a high temperature, even very negative transitions will be accepted, but as the temperature falls, the acceptance of such transitions will become increasingly rare. Occasionally accepting candidate solutions worse than the current solution helps the algorithm to avoid becoming trapped in a local optimum. The SA algorithm proceeds until the value of solutions ceases to increase. The LI procedure starts with the best solution identified through the SA algorithm and moves into the best solution within all possible solutions in its neighborhood. By doing this in successive iterations, until no further improvement can be found, the LI procedure can be expected to improve on the solution obtained by the SA algorithm. The implementation and development of an efficient hybrid algorithm of this type is explained in Zeferino et al. [16].

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. This water quality model is developed to manage oxygen-demanding wastes and the water quality parameter of interest is thus the DO concentration in the river.

3. 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 (see Figure 1). 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 (left) 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. In Figure 1 (right) is presented the spatial distribution of the populations (figures close to population centers 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 flowing for 50 km through the region from Country A (for 23 km) to Country B (for 27 km). The water quality standards defined for surface waters vary according to each 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 by Country A.

Because of the differences in wealth 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 intended to install primary WWTPs, with pollutant removal efficiencies around 25%. Country B attempts to fulfill its water quality standards by installing secondary WWTPs, with pollutant removal efficiencies around 90%.

The solutions for the wastewater systems of both countries and consequent surface water quality in the shared river depend on the management option applied. Each country can design its own system individually, or both countries cooperate in a transboundary wastewater planning applying coordination of pollution control.

[Insert Figure 1 approximately here]

3.1. SEPARATE SYSTEM FOR EACH COUNTRY

The first management option consists in 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.

3.2. TRANSBOUNDARY SYSTEM

For the transboundary system approach, two management options are considered for the solutions of the wastewater system: i) separate systems for each country with pollution coordination; and ii) an international system for the region.

The management option of separate system with pollution coordination consists in designing independent wastewater systems for Country A and Country B. The systems are designed with a cost minimization objective, aiming at guaranteeing the water quality in the river where the effluent is discharged. Each country considers not only the water quality standards defined for its reaches but also the ones defined by the neighbor country for the reach close to the border. This allows for the coordination of the pollution control.

The management option of an international system for the region consists in designing an integrated transboundary wastewater system for the entire region. In particular, an international WWTP is allowed to be constructed on the border between the two countries (Figure 1 – right). This can only be a secondary WWTP according to the most demanding requirements of Country B. The international system aims at guaranteeing the water quality in the river where the effluent is discharged according to the standards defined by both countries.

Such a large-scale planning at transboundary level might provide better environmental solutions, while taking advantage of scale economies. However, the country with fewer economic resources might not be interested in paying the additional cost of better treatment efficiencies, and thus the willingness to pay question arises. The cost sharing for the transboundary system solutions can be defined in several ways. For each management option of the transboundary system approach, two cost allocation principles are considered: the Polluter Pays Principle (PPP) and the Beneficiary Pays the Difference Principle (BPDP). The PPP requires countries to meet the full costs of their actions, bearing the costs of implementing pollution prevention and control measures to guarantee the transboundary water quality standards. However, when these standards are higher than required for one of the parts involved, it is reasonable that some of its costs are allocated to the other benefiting part. In this sense, through the BPDP the less-wealthy country pays only for guaranteeing its own relatively low standards, while the richer beneficiary pays the difference to bring it to its own higher standards.

4. RESULTS

The wastewater system for the case study region was solved for the three different management options considered. An SA algorithm enhanced with an LI procedure was used to solve the optimization model. The results obtained for each option are intended to be used as reference solutions for negotiation between the countries involved.

4.1. SEPARATE SYSTEM FOR EACH COUNTRY

The configuration of the solutions obtained when the wastewater system is designed separately for each country without coordination of pollution control is shown in Figure 2 (top). The respective costs are presented in Table 1. These are the minimum costs that each country would pay to collect and treat its wastewater while guaranteeing the respective water quality standards. The total discounted cost of Country A's wastewater system (11.41 M€) is about 42% lower than the cost obtained for Country B (19.62 M€). The main reason for this difference lies in the wastewater treatment. Country A uses only a primary WWTP, whereas Country B makes use of the more costly secondary WWTP. In addition, although Country A has a slightly larger population and requires one pump station, its region has a smaller area. This results in economies of density, perceptible in the lower cost of sewers, as the wastewater collected is larger but their total length is shorter.

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 2 (bottom) shows the DO concentrations along the transboundary river, including 20 km downstream of the region. 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 5.7 mg/L, which is 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) cannot be guaranteed. The minimum cost solution obtained for Country B has a single effluent discharge in the secondary WWTP installed at the node further downstream. But its water quality standards are guaranteed only for the last 4.5 km of river reaches.

[Insert Table 1 approximately here]

[Insert Figure 2 approximately here]

4.2. TRANSBOUNDARY SYSTEM

4.2.1. Separate system with pollution coordination

For the system designed separately for each country with coordination of pollution control, the configuration of the solution is shown in Figure 3 (top). The total joint costs are presented in Table 2, together with two alternative cost allocations for each country. The total joint costs correspond to the minimum values that both countries would pay together to collect and treat their wastewater separately while ensuring water quality standards across both countries. The total joint cost of the systems (35.73 M€) is about 15% higher than the sum of the costs of the separate solutions without pollution coordination. This cost increase is mainly due to the WWTP costs that originate from the new secondary WWTP installed in Country A where the largest part of its wastewater is treated.

The pollution coordination between the countries allows for the water quality standards to be guaranteed for both countries. Figure 3 (bottom) shows the DO concentrations along the transboundary river. The lowest DO concentration is around 6.8 mg/L, and occurs close to the border between the two countries. Therefore, the DO concentrations are always higher than the DO standards of 5.0 mg/L in Country A and 6.5 mg/L in Country B.

[Insert Table 2 approximately here]

[Insert Figure 3 approximately here]

The total joint costs of the system can be allocated to each country according to the PPP, that is, with each country paying its share for wastewater collection and treatment. The resulting costs correspond to the cost of the wastewater system to be built in the respective country (Table 2). The cost of Country's B wastewater system is the same as for the separate solution without pollution control because the water quality constraints of Country A are not binding the solution of Country B. However, in order to guarantee the standards of Country B, the wastewater system of Country A is considerably improved. Therefore, for Country A the costs increases 41%, from 11.41 M€ to 16.10 M€, due to the new and more expensive WWTP. This cost increase corresponds to 37% of its capital costs and 52% of its operating and maintenance costs.

The BPDP allocates the difference to the improved solution to the benefiting wealthier country (Table 2). This implies that Country A will only pay for the pollution abatement it was supposed to undertake anyway. Therefore Country A has the same cost as for the separate solution without pollution control (11.69 M€), because its water quality standards were already guaranteed. For Country B the costs increase 24% from 19.63 M€ to 24.32 M€. This corresponds to an increase of 21% in capital costs and 30% in operating and maintenance costs for Country B. This increase in total discounted costs (4.69 M€) is equal to the one that was allocated to Country A in the PPP and is now allocated to Country B. It corresponds to the "difference" to be paid by the beneficiary (the wealthier country) in order to attain its water quality goals.

4.2.2. International system for the region

The establishment of an international water regime allows for the coordination of pollution control but also possible cost savings. The solution obtained for the case study when the wastewater system is designed at international level is shown in Figure 4 (top). The respective international costs are presented in Table 3. In this solution, most wastewater generated in Country A and Country B are treated in a single international WWTP for secondary treatment. In addition, each country uses their own WWTPs, which is of primary treatment in Country A and secondary treatment in Country B. The total discounted cost of the system (35.60 M€) is slightly lower compared to the other transboundary solution that also guarantees the DO standards. This is due to some scale economies, which are not larger because the restrictive water quality standards require this solution to have the same amount of WWTPs.

Figure 4 (bottom) shows the DO concentrations along the reaches of the transboundary river. In this solution, the DO standard in Country A is largely guaranteed as there is only little wastewater discharged in its reaches. The DO standard for Country B is achieved, too. Likewise the separate solution with pollution coordination, the environmental advantages of this transboundary system are considerable.

[Insert Table 3 approximately here]

[Insert Figure 4 approximately here]

Using the PPP, the costs of the international system allocated to each country correspond to the cost of their own wastewater system to be built plus their share of the international WWTP in terms of the amount of wastewater treated there (Table 3). The total cost for Country A is slightly larger than for Country B, as it has a larger population. This difference is not greater because the additional WWTP owned by Country A is of primary treatment, thus cheaper than the secondary one of Country B. Compared to the separate solution without pollution coordination, the total costs increase 58% for Country A and decrease 10% for Country B. This is due to the improved treatment in Country A, and scale economies from the large international WWTP in Country B. Compared to both cost allocations of the separate solutions with pollution coordination, the international solution costs allocated through the PPP are always higher for Country A and lower for Country B.

Using the BPDP, the wealthier country bears the largest share of the international solution costs (Table 3). In this cost allocation alternative, the cost for Country A is again the same cost as the separate solution without pollution control (11.69 M€). The cost for Country B corresponds to the total cost of the international system (35.60 M€) net of the cost allocated to Country A, which it was supposed to spend anyway if it would have opted for the separate solution without pollution control. Consequently, the cost for Country B increases 23%, from 19.62 M€ to 24.19 M€, with 29% of these due to operating and maintenance cost from the larger WWTP. This is the price to pay in order to reach its water quality goals. Using the BPDP, a pertinent advantage of the international solution compared to the other transboundary solution is that Country B can directly manage the international WWTP rather than subsidize Country A to manage its own secondary WWTP.

5. CONCLUSION

This study presented a methodology for wastewater system planning across borders. The transboundary approach offers the coordination of pollution control, handling situations with upstream-downstream water conflicts. The proposed methodology contributes to 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. This paper explores an important direction of research owing to the technical challenges involved in the shift from the planning of separate systems for each country to a transboundary approach integrated into an optimization model.

The use of the proposed optimization model is important to gather and interpret information from a transboundary standpoint, building a foundation for policy decision-making. Results show that the transboundary solutions provide considerable environmental advantages, in particular by guaranteeing different water quality standards. The transboundary approach is important from the 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 costs are shared between the different parties involved was addressed according to the asymmetrical willingness to pay. Two extreme situations of cost allocation were analyzed. 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, legal, 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. Different treatment efficiencies in the WWTP and different water quality parameters can be studied, too. Future work will also include the uncertainty inherent to the quantitative emissions control, tax rates and system costs. Finally, the application to a real world case study will shed new light on the advantages of this type of approach.

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Captions for Figures and Tables

Figure 1. Topography (left) and spatial distribution of population and possible WWTP locations (right)

Figure 2. Configuration of the separate solutions for each country (top) and its dissolved oxygen concentrations throughout the river (bottom)

Figure 3. Configuration of the separate solutions with pollution coordination (top) and its dissolved oxygen concentrations throughout the river (bottom)

Figure 4. Configuration of the international solution (top) and its dissolved oxygen concentrations throughout the river (bottom)

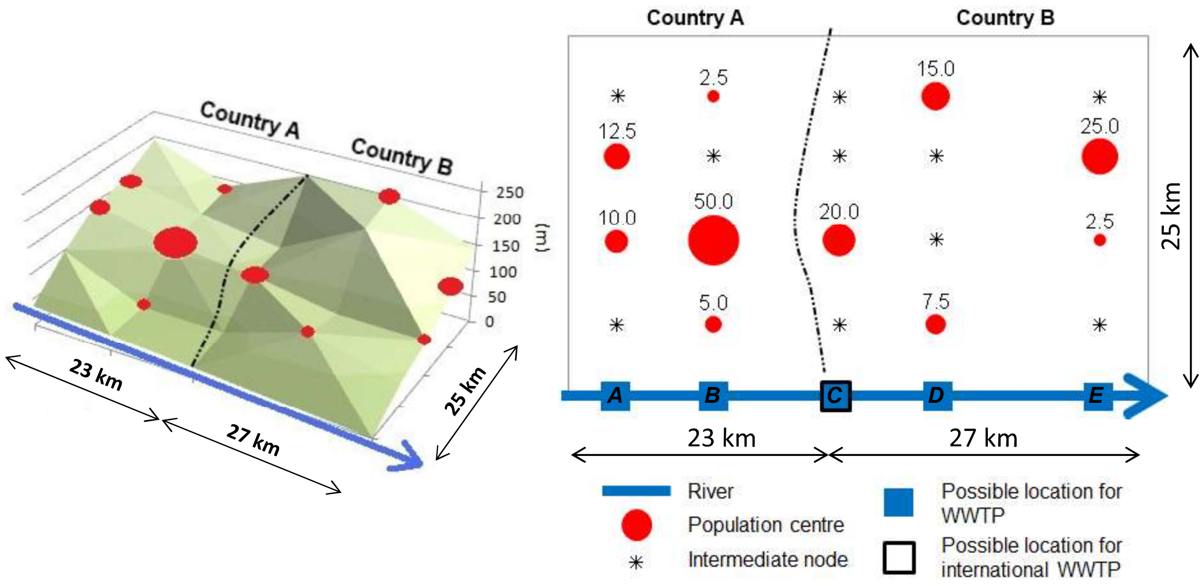
Table 1. Cost of the separate solutions for each country

Table 2. Cost of the separate solutions with pollution coordination and alternative cost allocations

Table 3. Cost of the international solution and alternative cost allocations

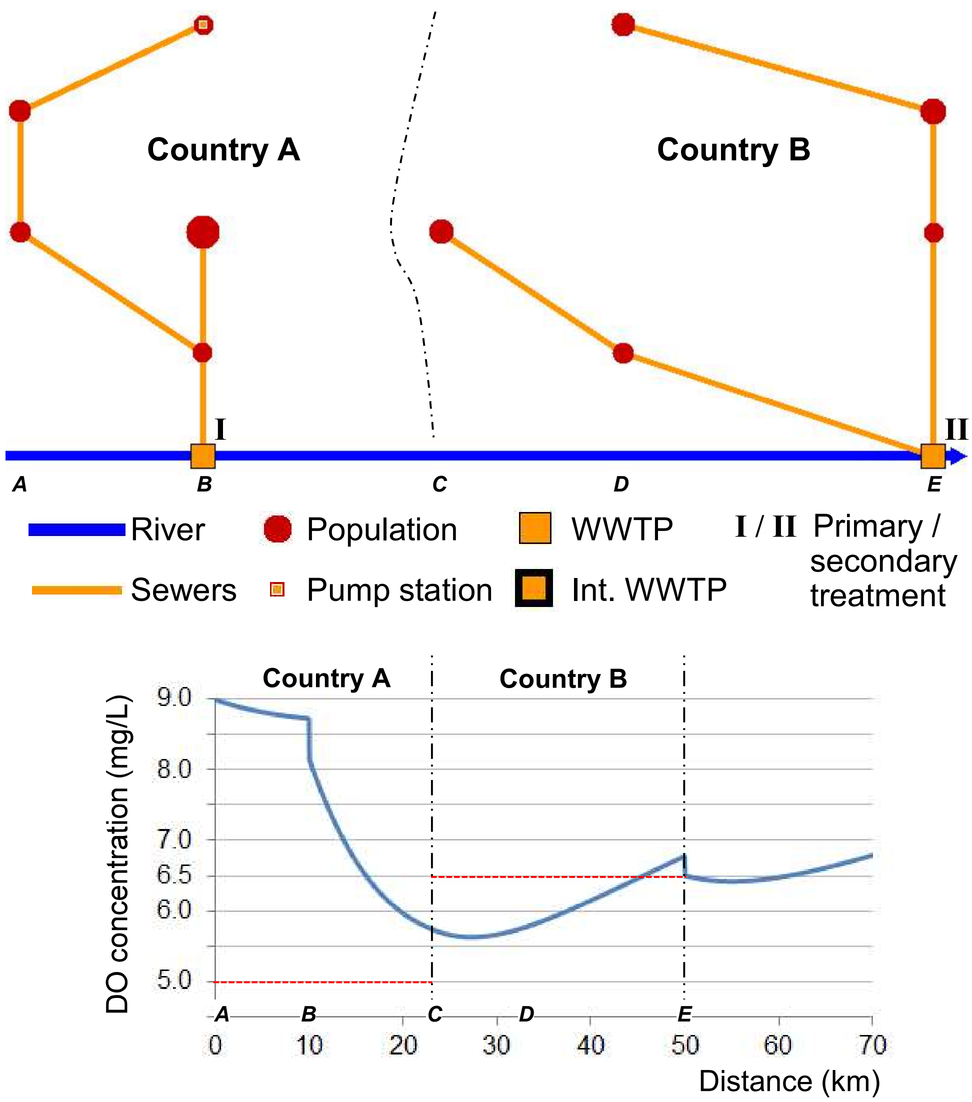
Figure

Figure 1.



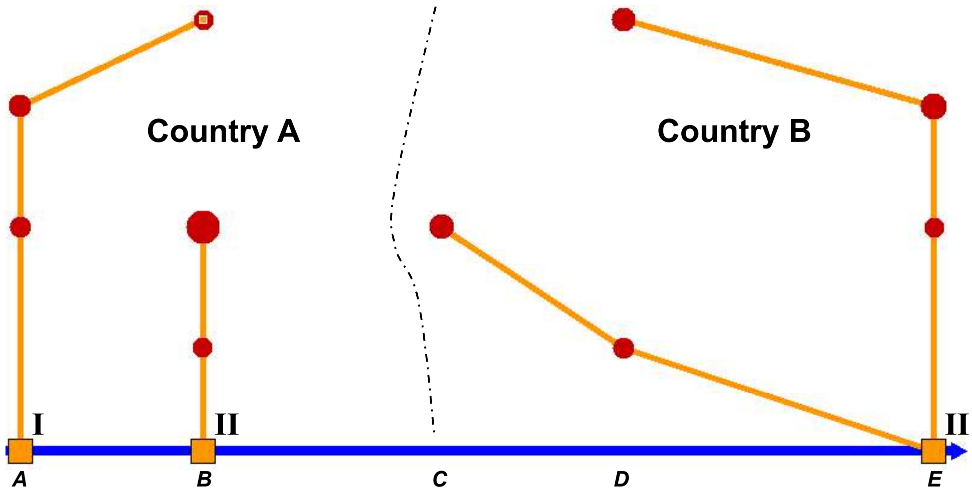
Figure

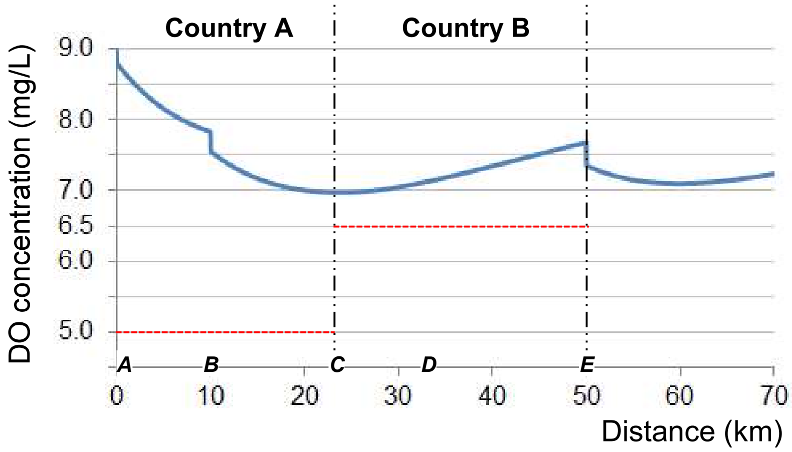
Figure 2.



Figure

Figure 3.





Figure

Figure 4.

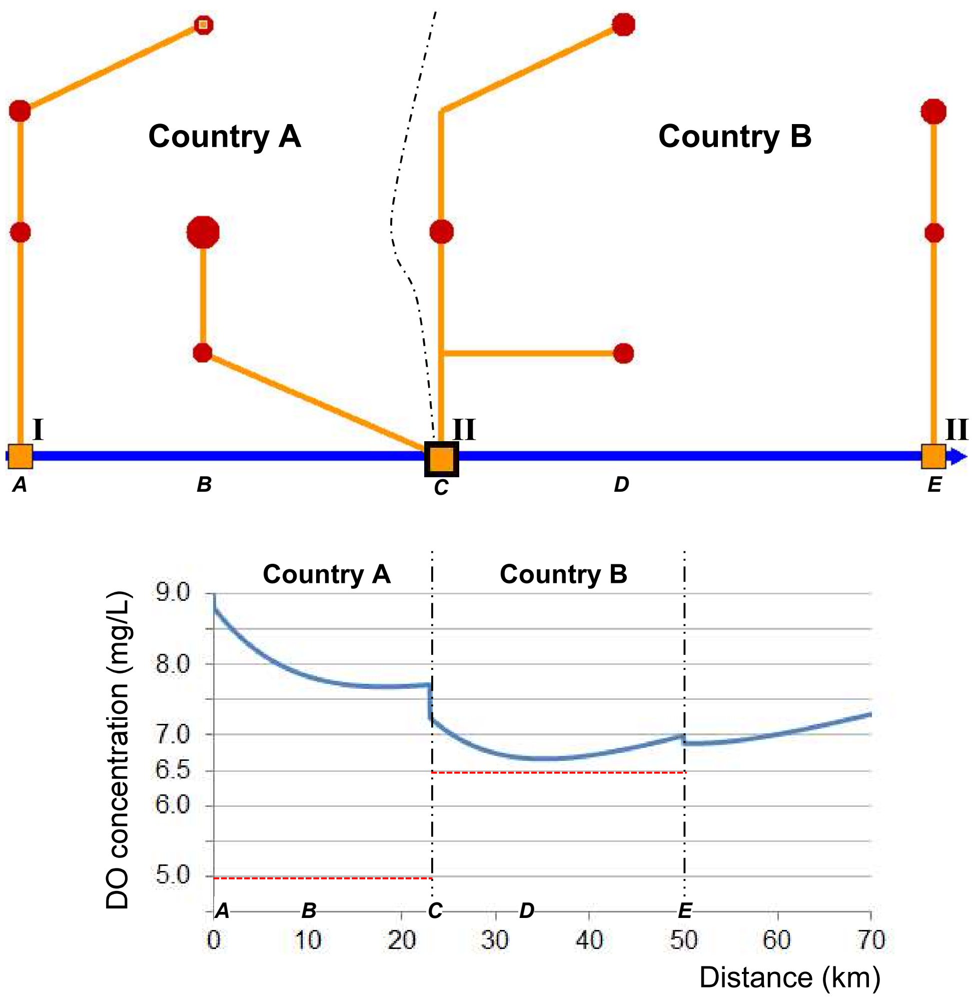


Table_1

Table 1.

	Infrastructure discounted costs (M€)			Total System costs		
	Sewers	**Pump stations**	**WWTP**	**Capital (M€)**	**Operating (k€/year)**	**Discounted (M€)**
Country A	6.06	0.11	5.24	8.14	240.94	11.41
Country B	10.14	0.00	9.48	14.01	412.71	19.62
Total	16.21	0.11	14.72	22.15	653.65	31.04

Table_2

Table 2.

	Infrastructure discounted costs (M€)			Total System costs		
	Sewers	**Pump stations**	**WWTP**	**Capital (M€)**	**Operating (k€/year)**	**Discounted (M€)**
Total	16.01	0.11	19.60	25.15	778.20	35.73
PPP		**Country A**		11.14	365.49	16.10
		Country B		14.01	412.71	19.62
BPDP		**Country A**		8.14	240.94	11.41
		Country B		17.01	537.26	24.32

Table_3

Table 3.

	Infrastructure discounted costs (M€)			Total System costs		
	Sewers	**Pump stations**	**WWTP**	**Capital (M€)**	**Operating (k€/year)**	**Discounted (M€)**
International	16.36	0.11	19.13	25.05	776.68	35.60
PPP	**Country A**			11.91	377.05	18.03
	Country B			13.14	399.62	17.58
BPDP	**Country A**			8.14	240.94	11.41
	Country B			16.91	535.74	24.19