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OPTIMIZATION OF WATER RESOURCES SYSTEMS USING MULTI-OBJECTIVE EVOLUTION STRATEGIES

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Abstract. *This paper deals with the development of a new multi-objective evolution strategy in combination with an integrated pollution-load and water-quality model. The optimization algorithm combines the advantages of the Non-Dominated Sorting Genetic Algorithm and Self-Adaptive Evolution Strategies. The identification of a good spread of solutions on the pareto-optimum front and the optimization of a large number of decision variables equally demands numerous simulation runs. In addition, statements with regard to the frequency of critical concentrations and peak discharges require continuous long-term simulations. Therefore, a fast operating integrated simulation model is needed providing the required precision of the results. For this purpose, a hydrological deterministic pollution-load model has been coupled with a river water-quality and a rainfall-runoff model. Wastewater treatment plants are simulated in a simplified way. The functionality of the optimization and simulation tool has been validated by analyzing a real catchment area including sewer system, WWTP, water body and natural river basin. For the optimization/rehabilitation of the urban drainage system, both innovative and approved measures have been examined and used as decision variables. As objective functions, investment costs and river water quality criteria have been used.*

1 INTRODUCTION

The implementation of the European Water Framework Directive includes new provisions to regulate pollution from diverse substances and sources [4]. This comprises the establishment of a combined approach, which permits the use of both Environmental Quality Standards and fixed Emission Limit Values [10]. The dominant objective of the WFD is to achieve a “good ecological and chemical status” by means of river basin management plans.

Research results have shown that optimum management of the individual components of the urban water system does not necessarily yield optimum performance of the entire system [9]. For example, minimization of the total overflow volume does not automatically result in optimum water quality [21]. Therefore, an integrated approach accounting for various sources of pressures and impacts on water bodies is required. Important components to assess the “good ecological and chemical status” are chemical and physicochemical water quality parameters as well as morphological and biological characteristics of the water body.

Expanding urbanized areas cause amplification of infrastructure for urban drainage. In turn this stands for a further impact on water resources balance, quality and consequently on the ecological and chemical status. Alteration of river flow dynamics e.g. increase of high frequent flood events and impairment of water quality due to pollution loads comprising mainly nutrients, BOD and COD are known negative effects [3].

Mitigation measures can be applied in different fields. As far as urban drainage is concerned a multitude of approved and innovative measures are available [13]. With respect to scarce financial resources, investments have to be cost-effective. A major objective of water resources management and associated planning process is a careful analysis of impacts, costs and benefits of different measures.

In this context, computer based simulation models are convenient and generally accepted planning tools. However, most of the existing models only address sub-systems of the total system considered [1]. The demand for a holistic assessment requires concepts with respect to the integrated application of available simulation models or tools [8].

In addition, most of the suitable measures interact with respect to runoff and load e.g. additional storage volume, adjustment of throttle discharge and decentralized infiltration. Therefore, an optimization of urban drainage systems regarding monetary and ecological objectives is complex and, if at all, only possible with substantial expert knowledge and appropriated software tools [15].

2 METHODOLOGY

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According to the requirements described, this paper presents an integrated optimization and simulation tool. The system developed consists of an integrated modular simulation model including rainfall runoff, pollutant-load, wastewater treatment plant and water-quality modules and a multi-objective evolutionary algorithm.

2.1 Multi-objective evolution strategy

Classical optimization methods use a point-by-point approach, where one solution in each iteration is modified to a different one. Hence, the result is also a single optimized outcome. Therefore, it is necessary to convert the task of finding multiple trade-off solutions in a multi-objective optimization to one of finding a single solution of a transformed single-objective optimization problem. For this purpose, a relative preference vector is used to scale multiple objectives into a single-objective optimization problem.

Evolutionary Algorithms mimics evolutionary principles to search optimal solutions. Unlike classical methods, they use a population of solutions in each iteration instead of a single solution. Therefore, the result of an Evolutionary Algorithm is also a population of solutions. If an optimization problem has multiple optimal solutions Evolutionary Algorithms can be used to capture multiple optimal solutions in its final population. This ability makes Evolutionary Algorithms unique in solving multi-objective optimization problems. Therefore, they are ideal approaches to solve multi-objective problems in the context of water-quality oriented optimization of urban water systems. This procedure is illustrated in figure 1.

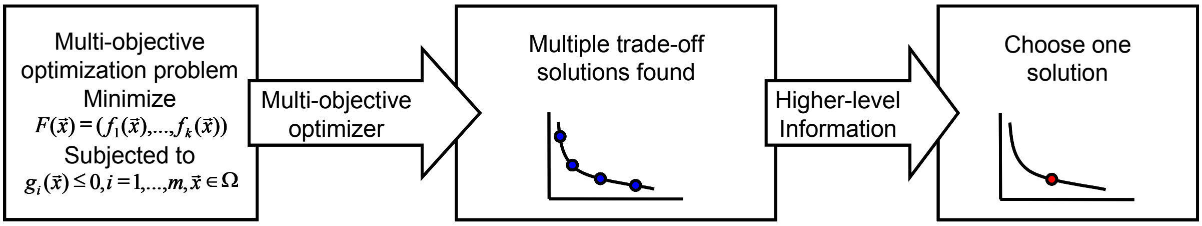

Figure 1. Multi-objective optimization procedure

As optimization algorithm a multi-objective evolution strategy has been developed. It is based on the concepts of domination and pareto optimum [27]. A pareto optimal solution has the characteristic that one objective cannot be improved without worsening a different one. The developed algorithm combines the advantages and methods of the Non-Dominated Sorting Genetic Algorithm [7], the Strength Pareto Evolutionary Algorithm [29] and classical Self-Adaptive Evolution Strategies [22]. In addition, it contains further newly developed approaches increasing convergence and robustness of the algorithm. The efficiency of the new algorithm has been proven and emphasized by a comparison with established evolutionary algorithms based on Zitzlers's test problems and results [28].

2.2 Integrated urban catchment model

Evolutionary Algorithms require objective values that represent the effects of different measures on the analysed criterions. These values have to be calculated with simulation models normally. In the context of water-quality oriented objectives, a concept with respect to the integrated application of simulation models is necessary. In addition, the finding of a good spread of solutions on the pareto-optimum front and optimizing a large number of decision variables demands a large number of simulations. Furthermore, statements with regard to the frequency of critical concentrations and peak loads require continuous long-term simulations [26]. Therefore, a fast and robust integrated simulation model is needed providing the required precision of results.

For this, only the significant impacts and processes were taken into account [18]. All modelling approaches were chosen according to the principle as detailed as necessary, as simple as possible [24]. A consistent set of model parameters in all subsystems [19] and coordinated spatial and temporal scales [23] are used. It was advisable to develop an adapted modular simulation tool based on the concepts and complexity level of the used sewer system model.

The integrated simulation model developed consists of four subsystems, the upper catchment, the urban sewer system, the treatment plant and the receiving water body. An established hydrological deterministic pollution-load model [16, 17] has been coupled with a river water-quality module, a treatment plant module and a rainfall-runoff model. As result emission as well as river water quality oriented objectives can be analysed. All quantitative and qualitative processes are calculated time variable on a small scale (minutes).

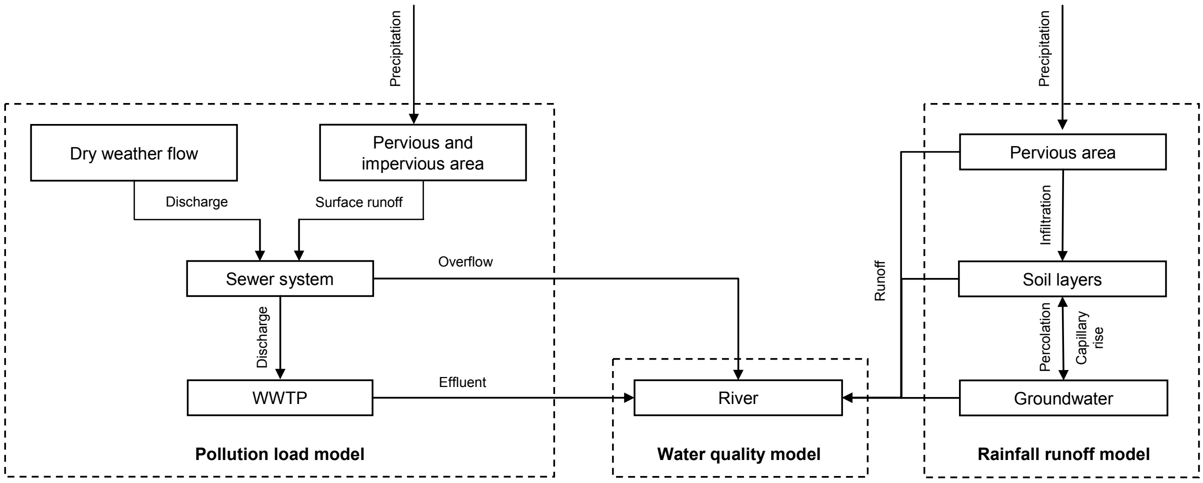

Figure 2. Structure of the integrated simulation model

The pollution load simulation model is a site-specific and component-detailed hydrological deterministic rainfall and pollution load model. It is a long-term simulation model and computes the dominant characteristics for the assessment of the effect of overflow structures on receiving water bodies either in existing or planned drainage systems. The simulated processes include runoff formation and concentration from pervious and impervious areas, superposition of dry-weather flow and storm water runoff in collecting pipes and structures as well as translation and retention of hydrographs and pollutographs in sewer systems. A multitude of BMP can be represented in the model. The specification of the pollution concentrations of the particular partial currents is based on three components. The imported water and surface runoff of pervious areas is considered as unloaded. The concentration of the surface runoff of impervious areas is calculated due to accumulation and wash-off. The dry weather flow is defined with its time variable pollution concentration and flow.

The water quality module calculates transport, storage and distribution of volume and load in river systems using non-linear hydrological reservoir cascades in combination with a plug flow approach. The water quality is calculated with reaction kinetics of first order including the parameters DO, BOD/COD and nitrogen [5]. The developed model has no restrictions with regard to temporal and spatial resolutions. Hence, an optimal adaptation to the spatial and temporal scales of the pollution load model is possible.

The wastewater treatment plants are simulated in a simplified way. For dry weather flow, average outflow concentrations are used. For storm water flow, functions can be defined for an outflow concentration rise. Retention is simulated by a linear reservoir [14].

The upper boundary condition of the water body is simulated with a rainfall-runoff model including soil moisture simulation based on a non-linear model, relating the dominant processes infiltration, percolation and actual evapotranspiration to soil moisture. Model structure is physically based, yet avoiding numerical solutions [12]. The used modelling approaches belong to the same categories as the used approaches of the pollution load model. Therefore, consistent sets of modelled parameters and coordinated spatial and temporal scales are provided in all sub models.

2.3 Integrated optimization and optimization tool

The integrated simulation model and the multi-objective optimization algorithm were implemented in a modular common software shell providing fully automatic interfaces for simulation and optimization tool, databases for input data and simulation as well as optimization results, user interfaces for data input, result analysis and tools for control the optimization process. Furthermore, a simple approach for distributed computing in heterogeneous networks is implemented. The chosen modular structure and the fact that evolution strategy does not make assumptions on continuity of the objective functions and does not require information on its derivatives allows a strict separation of optimization algorithm and simulation model. Therefore, modification or exchange of the simulation model is easily possible.

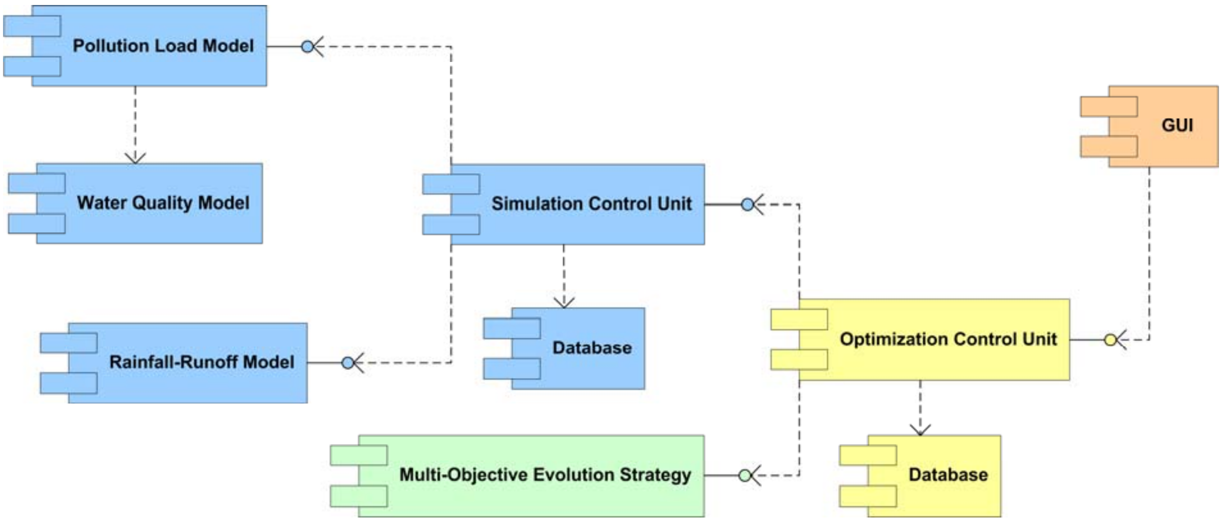

Figure 3. Structure of integrated simulation and optimisation system

3 TEST CASE AND RESULTS

The coupled simulation and optimization tools have been applied to a real catchment area including natural and urban areas, sewer system, WWTP and water body testing the functionality of the developed system (total area 38 km^2, total urbanized area 8.8 km^2, examined urbanized area 3.8 km^2, inhabitants 42,000 respectively 19,000).

As objective functions, investment costs [11] and river water quality criteria have been used simultaneously. The definition of the object functions is oriented at the suggestions of BWK [2]. For the assessment of acute loads due to combined sewer overflows hydraulic stress (permitted critical annual overflow), maximum ammonia concentration (< 0.1 mg/l) and minimum dissolved oxygen (> 5 mg/l) are considered relevant. For the optimization, maximum dissolved oxygen deficit instead of concentration is used. The analysis of the current state shows significant deficits for all objectives. The discrepancy is particularly dramatic for the annual overflow rate (0.75 m³/s contrary to 10.1 m³/s). Nevertheless, also the maximum ammonia and oxygen concentration exceeds respectively falls below the limit values.

For the optimization of the urban drainage system and rehabilitation of the water body several innovative and traditional measures have been selected (additional storage volume, decentralized infiltration, optimal adjusting of throttle discharge, retention soil filters). These measures have been used as decision variables within the optimization algorithm. Any constraints on the decision variables (e.g. upper and lower limits) are included in the definition of the feasible parameter set. Accessory constraints (e.g. specific storage volume, stacking height for retention soil filter) have been included in the definition of the feasible objective space, based on a modified version of the used concept of domination and pareto optimum [6]. Figure 4 shows the examined urban catchment area with the WWTP and overflow structures as well as the selected measures.

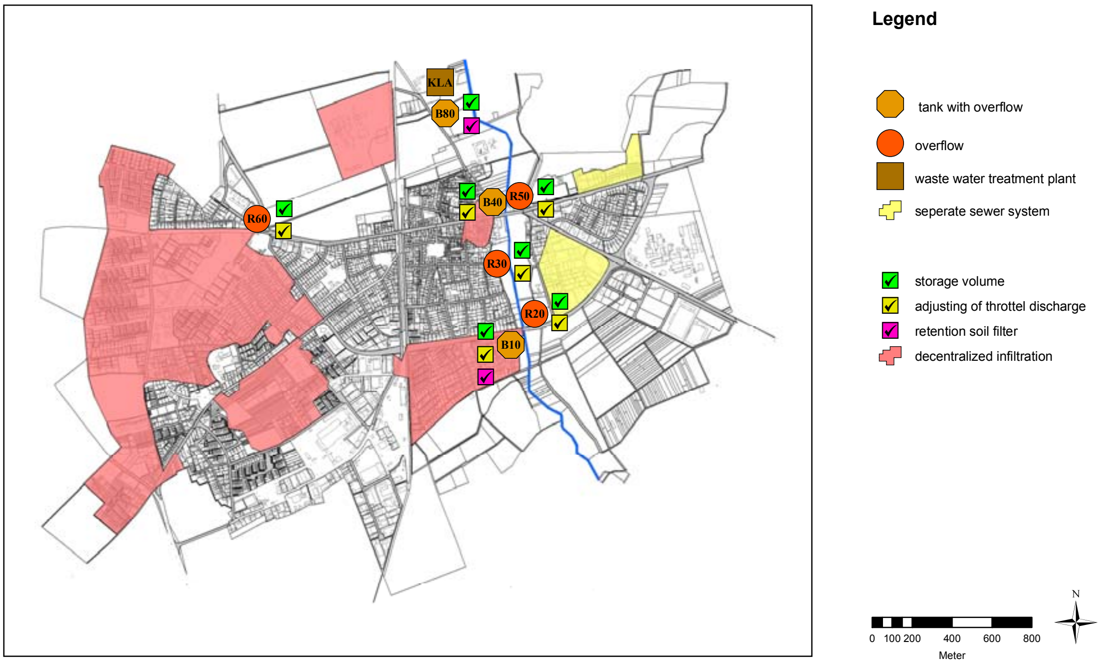

Figure 4. Examined urban catchment area

It results a nonlinear complex optimization problem with four objectives, eleven boundary conditions and thirty-seven decision variables. The optimization was carried out using 500 Generations with 75 offspring and 25 parents. Each evaluation of the objective functions and constraints requires three simulations (annual series of block precipitation for the maximum overflow rate, one month continues long-term simulation for the maximum dissolved oxygen deficit and ammonia concentration and one year continues long-term simulation for the constraints, e.g. stacking height for retention soil filters). Following from this 37500 Iterations with 112500 simulations were needed.

In figure 5, the results of the optimization are shown in a scatter-plot matrix. All possible twelve pairs of plots (two-dimensional) among the objective space (four-dimensional) are shown. The diagonal sub-plots mark the axis for the corresponding off diagonal. Thus a plot in the (i,j) position of the matrix is identical to the plot in the (j,i) position, except the plot is mirrored. The results represent the identified pareto optimum approximations, i.e. only optimal trade-off solutions are plotted. All solutions have the characteristic that one objective cannot be improved without worsening a different one.

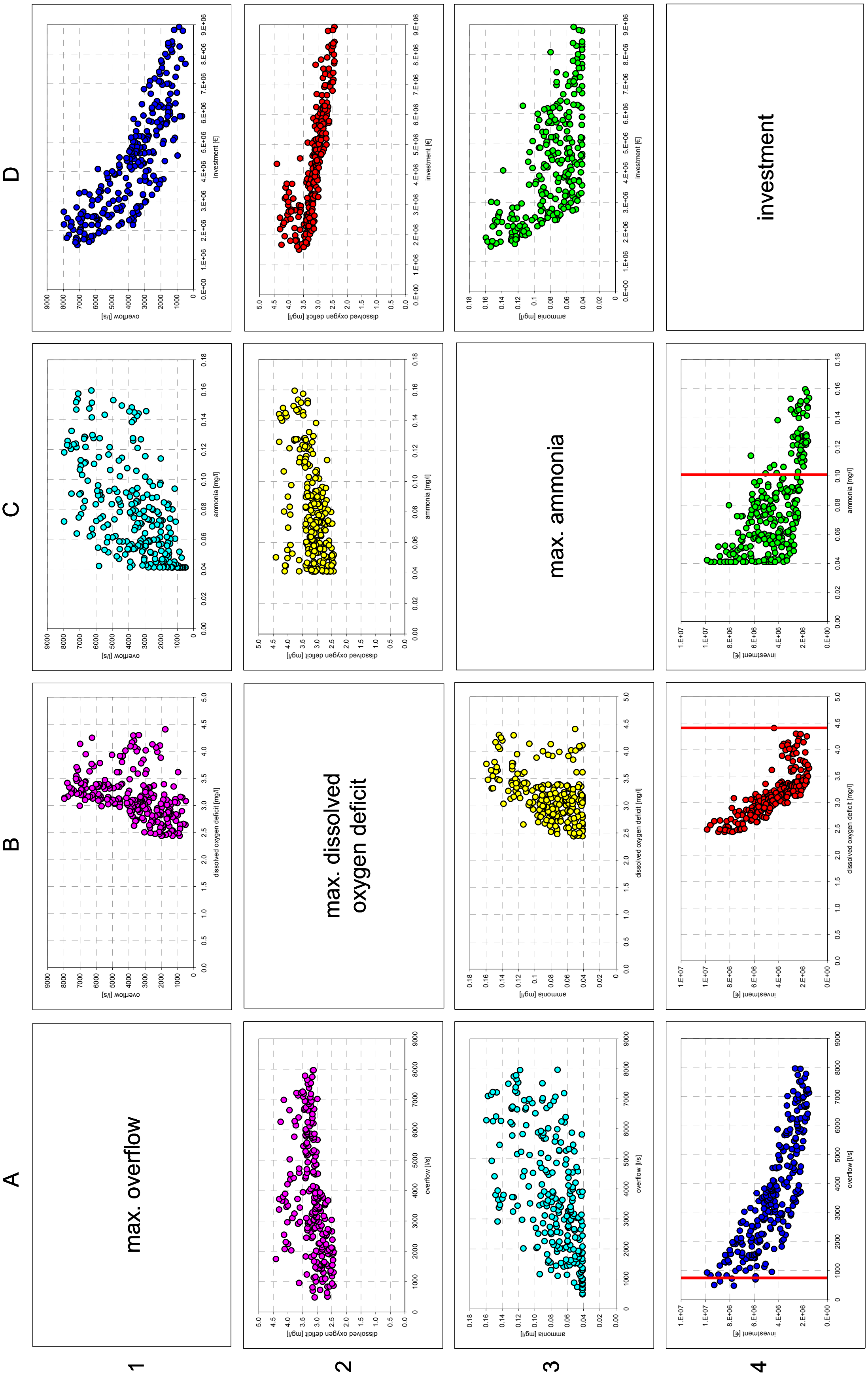

Figure 5. Optimization results

In line 4/column D the investments are set against the annual overflow rate and respectively the ammonia concentration and the dissolved oxygen deficit. Red lines mark the limit values. To fulfil all limit values at least 5.5 million Euros are necessary, to fulfil only the water quality limits approximately 2 million Euros are needed. The minimum reachable oxygen deficit and ammonia concentration approximate the inflow concentrations of the upper boundary condition, for this 7.5 respectively 3 million Euros are required. The dominant problem is the hydraulic load.

Plot (A,2) and (A,3) set the overflow rate against the oxygen deficit and the ammonia concentration. It gets clear, that a reduction of the overflow rate does not result in less ammonia concentrations and oxygen deficit absolutely. This applies particularly to ammonia. Plot (B,3) confirms this issue.

All decision variables (e.g. throttle discharge, degree of decentralise infiltration) of all solutions are available in a database supporting a fast and effective analysis. This facilitates the identification of optimal combination of measures. In addition, the optimal choice of location of different measures is possible.

4 CONCLUSIONS

The optimization method and the integrated simulation model have proved to be both robust and efficient. Particularly in complex cases, the optimization and simulation tool facilitates a fast optimization. The identified pareto optimum solutions provide an improved basis for discussions among stakeholders involved in decision processes. Nevertheless, a more realistic simulation of water quality processes is desirable. The performance of the wastewater treatment plant during storm events and the effects on the water quality accordingly are simulated in a simplified way. Therefore, a more detailed wastewater treatment plant module is necessary [20]. In the same way consideration of additional measures like RTC and maximum treatment plant inflow capacity [25] requires a more detailed simulation of sewer systems (hydrodynamic flow routing) as well as treatment plants (dynamic simulation).

The described integrated simulation and optimization tool requires extensive computing time. On this account, a hydrodynamic calculation of the sewer system and a dynamic simulation of treatment plant now are practically infeasible even with the implemented simple distributed computing approach. However, the evolution strategy is requiring coupled parallel-distributed computing systems. Otherwise, a more detailed simulation without reducing the complexity of the objectives and constraints and/or the extending of the simulation period is not possible.

The user of the system nevertheless limits the quality of the results. An uncritical consideration can result only apparently optimal solutions. The interpretation of the solutions requires a substantial expert knowledge. The best software also cannot replace the creativity of the engineer. However, it can be an effective support.

REFERENCES

[1] Andersen, H. S., H. Tamasauskas und O. Mark, The Full Urban Water Cycle - Modelling with MIKE URBAN. *6th International Conference on Urban Drainage Modelling*, Dresden, 2004.

[2] BWK, *Merkblatt 3. Ableitungen von immissionsorientierten Anforderungen an Misch- und Niederschlagswassereinleitungen unter Berücksichtigung örtlicher Verhältnisse*. Düsseldorf: Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau e. V., 2001.

[3] BWK, *Begleitband zu dem BWK-Merkblatt 3. Ableitungen von immissionsorientierten Anforderungen an Misch- und Niederschlagswassereinleitungen unter Berücksichtigung örtlicher Verhältnisse*. Düsseldorf: Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau e. V., 2003.

[4] CEC, *Directive 2000/60/EC of the European Parliament and the Council of 23 October 2000, establishing a framework for Community action in the field of water policy, 2000.*

[5] Chapra, S. C., *Surface water-quality modeling*. New York: McGraw-Hill, 1997.

[6] Deb, K., *Multi-Objective Optimization using Evolutionary Algorithms*. Wiley-Interscience Series in Systems and Optimization. Chichester: John Wiley & Sons, 2001.

[7] Deb, K., S. Agrawal, A. Pratab und T. Meyarivan, *A Fast Elitist Non-Dominated Sorting Genetic Algorithm for Multi-Objective Optimization: NSGA-II*, KanGAL report 200001. Kanpur: Indian Institute of Technology, 2000.

[8] Erbe, V., T. Frehmann, W. F. Geiger, P. Krebs, J. Londong, K.-H. Rosenwinkel und K. Seggelke, Integrated Modelling as an Analytical and Optimisation Tool for Urban Watershed Management. *Water Science and Technology* **46** (6-7): 141-150, 2002.

[9] Fronteau, C., W. Bauwens und P. A. Vanrolleghem, Integrated Modelling: Comparison of State Variables, Process and Parameters in Sewer and Wastewater Treatment Plant Models. *Water Sciences and Technology* **36** (5): 373-380, 1997.

[10] Griffiths, M., *The European Water Framework Directive: An Approach to Integrated River Basin Management*. European Water Management Online, EWA [URL: http://www.ewaonline.de/journal/online.htm], 2002.

[11] Interwies, E., D. Borchardt, A. Kraemer, N. Kranz, B. Görlach, S. Richter, J. Willecke und T. Dworak, *Grundlagen für die Auswahl der kosteneffizientesten Maßnahmenkombinationen zur Aufnahme in das Maßnahmenprogramm nach Artikel 11 des Wasserrahmenrichtlinie - Handbuch.* Texte // Umweltbundesamt; 04,2 Umweltbundesamt, 2003.

[12] Lohr, H., *Simulation, Bewertung und Optimierung von Betriebsregeln für wasserwirtschaftliche Speichersysteme*. Mitteilungen 118. Darmstadt: Institut für Wasserbau und Wasserwirtschaft, Technische Universität Darmstadt, 2001.

[13] Mehler, R. und M. Ostrowski, Comparison of the Efficiency of Best Stormwater Management Practise in Urban Drainage Systems. *Water Science and Technology* **39** (9): 269-276, 1999.

[14] Muschalla, D., Optimization Potential of Sewage Systems. *British Hydrological Society Conference: Science and Practice for the 21st Century*, London, 2004.

[15] Muschalla, D., Integrated Modeling and Multi-Objective Evolution Strategy as a Method for Water Quality Oriented Optimization of Urban Drainage Systems. *10th International Conference on Urban Drainage*, Copenhagen, Denmark, 2005.

[16] Muschalla, D. und M. W. Ostrowski, *Leitfaden zur effizienten und sicheren Beurteilung von Schmutzfrachtberechnungen mit dem Modell SMUSI*. Wiesbaden: Hessisches Ministerium für Umwelt, ländlichen Raum und Verbraucherschutz, 2004.

[17] Ostrowski, M. W., R. Mehler und A. Leichtfuß, *Dokumentation des Schmutzfrachtmodells SMUSI Version 4.0*. Darmstadt: Institut für Wasserbau und Wasserwirtschaft, Technische Universität Darmstadt, 1998.

[18] Rauch, W., H. Aalderink, P. Krebs, W. Schilling und P. Vanrollerghem, Requirements for Integrated Wastewater Models - Driven by Receiving Water Objectives. *Water Science and Technology* **38** (11): 97-104, 1998.

[19] Rauch, W., J.-L. Bertrand-Krajewski, P. Krebs, O. Mark, W. Schilling, M. Schütze und P. A. Vanrolleghem, Deterministic Modelling of Integrated Urban Drainage Systems. *Water Science and Technology* **45** (3): 81-94, 2002.

[20] Rauch, W. und P. Harremoës, The Importance of the Treatment Plant Performance During Rain to Acute Water Pollution. *Water Science and Technology* **34** (3-4): 1-8, 1996.

[21] Rauch, W. und P. Harremoës, Genetic Algorithms in Real Time Control Applied to Minimise Transient Pollution from Urban Wastewater System. *Water Resources* **33**: 1265-1277, 1999.

[22] Rechenberg, I., *Evolutionsstrategie '94*. Werkstatt Bionik und Evolutionstechnik 1. Stuttgart: frommann-holzboog, 1994.

[23] Schmitt, T. G. und W. C. Huber, The Scope of Integrated Modeling - System Boundaries, Sub-Systems, Scales and Disciplines. *10th International Conference on Urban Drainage*, Copenhagen, Denmark, 2005.

[24] Schütze, M. und J. Alex, Suitable Integrated Modelling - Based on Simplified Models. *6th International Conference on Urban Drainage Modelling*, Dresden, Germany, 2004.

[25] Schütze, M., T. B. To, U. Jumar und D. Butler, Multi-Objective Control of Urban Wastewater Systems. *15th IFAC World Congress*, Barcelona, Spain, 2002.

[26] Schütze, M., P. Willems und G. Vaes, Integrated Simulation of Urban Wastewater Systems - How Many Rainfall Data do we need? 9th *International Conference on Urban Drainage*, Portland, USA, 2002.

[27] Veldhuizen, D. A. V. und G. B. Lamont, Multiobjective Evolutionary Algorithms: Analyzing the State-of-the-Art. *Evolutionary Computation* **8** (2): 125-148, 2000.

[28] Zitzler, E., K. Deb und L. Thiele, Comparison of Multiobjective Evolutionary Algorithms: Empirical Results. *Evolutionary Computation Journal* **8** (2): 125-148, 2000.

[29] Zitzler, E., M. Laumanns und L. Thiele, *SPEA2: Improving the Strength Pareto Evolutionary Algorithm*. Computer Engineering and Networks Laboratory (TIK), Swiss Federal Institute of Technology (ETH), Zürich. TIK-Report No. 103, 2001.