

INNOVATIVE SIMULATION AND OPTIMISATION TOOLS FOR BASINWIDE URBAN STORMWATER MANAGEMENT

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ABSTRACT

Traditionally urban and rural water management were carried out by different sectors of water resources engineering, partly even with rather different academic background like geography and civil engineering. The paradigm of integrated water resources development and management, however, requires basin wide considerations of water resources such as determined by the European Water Framework Directives or the US Clean Water Act. Decision making in water management has been widely and successfully supported by mathematical simulation and optimisation techniques during the last 40 years in different sectors. The change of paradigm is now asking for better integration of formerly sectoral submodels into a common combined toolbox. For economic reasons it is necessary to widely rely on existing submodels and to link them together by efficient interfaces. Another change of paradigm can be seen in the use of available technology. While over decades standard water technology has been supplied leaving little space to alternative solutions, it seems to be timely to go for individual optimum solutions, taking into account a set of multiple criteria for assessment of alternatives in the sense of sustainable development. The paper will demonstrate the results of recent developments in general and those by the authors in particular.

Key words: basinwide water management, integrated modelling and optimisation

1. INTRODUCTION

Within the last ten years integrated basinwide analysis has become an important paradigm in sustainable water resources planning and management with the European Water Framework Directive as an important driving force. During a relatively short time span science and technology has to react to this paradigm by developing and providing adequate planning and management tools. Formerly, separated simulation models were used in parallel to analyse the effect of constructional and management measures on water quantity and quality in rural and urban areas. These stand alone models were based on quite different time and space scales.

So far, mathematical optimisation methods in urban water management have been mostly restricted to the academic field, as practical decisions were mainly based on standard design rules simply aiming at fixed emission control limits only considering partly economic boundary conditions and the ecological state of receiving waters. The simultaneous consideration of different, often contradictive planning objectives such as ecologic maximisation and economic minimisation and the integrated basinwide analysis has made the decision process difficult and time consuming, calling for multi-criteria optimisation techniques.

The hydrology group at the authors' home university has made several practice oriented contributions to integrated simulation and optimisation techniques for basinwide stormwater management of which two simulation and one optimisation approaches will be presented in this paper.

The first initiative deals with the realisation of integrated rural and urban simulation models (Klawitter, 2006). In this research, two existing modelling approaches were modified and coupled in one GIS based shell. Urban areas are modelled with a stormwater management model. Data sets for most communities in the Federal State of Hesse are readily available. Rural areas are simulated with a raster GIS based physically oriented hydrological model, in which urban areas were cut out and stored in the urban GIS layer. Contact points between urban and rural water systems such as stormwater overflows or sewage treatment plants are defined to allow for the interaction between subsystems.

The maximum size of river basins is about 300 km², which can still be handled with front end office computers. The advantage of this coupled model is the simulation of all urban point sources (water and pollutants/nutrients) at a high spatial and temporal resolution along the river course.

The aim of the second study was the development of a new multi-objective evolution strategy in combination with an integrated pollution-load and water-quality model to optimize urban wastewater systems in an integrated view (Muschalla 2006a). The functionality of the optimization and simulation tool has been validated by analysing 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, hydraulic parameters and river water quality criteria have been used. It has to be stressed that these research activities are closely related to urgent questions which have to be answered by the water administration agencies in the Federal State of Hesse. Both case studies stem from the southern region of Hesse.

2. OBJECTIVES

Instead of applying local standard technology future water management asks for the identification of individual sets of integrated basinwide best management options to achieve a set of multiple targets in the sense of sustainable development. This requires the mathematical modelling of integrated water resources systems to consider feedback controls between different system elements. At the same time techniques are needed to identify best solutions among a huge number of potential feasible solutions. It was the objective of the authors to develop such simulation and optimisation techniques mainly based on existing modules with as few modifications as possible and to demonstrate their functionality by means of real world case studies. The development of these decision support tools was supposed to be imbedded in the regionally available information and data base in the Federal State of Hesse, which might be considered representative for the whole of Germany, but not necessarily for Europe.

3. METHODOLOGY

Incidentally the development of integrated basinwide models started from two sides. In the first project the development started from meso-scale hydrological basin model, which can be named a top-down approach. Traditionally, in such models urbanisation is represented in a very simple and aggregated manner. Within the development urban parts were cut out and replaced by a detailed urban pollution load model representing flows at higher temporal resolution to achieve adequate physical representation and accuracy. The second project started from the same urban pollution load model, which was extended to the receiving water bodies and linked to the overall catchment via an upstream interface defining flow and quality conditions, either through measured time series or by hydrological catchment modelling of headwaters. This can be rather considered as a bottom-up approach.

3.1 Linking a rural with an urban model

The first approach followed by Klawitter (2006) started from GIS raster based catchment modelling of small river basins initially developed by Lempert (2000). It soon became evident that the adequate consideration of urbanised areas with well developed infrastructure was very much limited within a rigid raster model. Fortunately, in the Federal State of Hesse in Germany reliable data sets are available for most of the existing urban drainage systems, which could be used as an information and data base for combined simulation. The first option was to use these data sets to estimate aggregated parameters for a consistent overall raster model. However, the uncertainty involved in this aggregation combined with limitations to represent important physical processes such as sewer transport and combined sewer overflows led to the selection of a second option. This option is based on a two layers –two models concept. The rural areas are simulated with a raster GIS based physically oriented hydrological model, in which urban areas were cut out and stored in the urban GIS layer. Contact points between urban and rural water systems such as stormwater overflows or sewage treatment plants are defined to allow for the interaction between subsystems. This concept is illustrated in Figure 1.

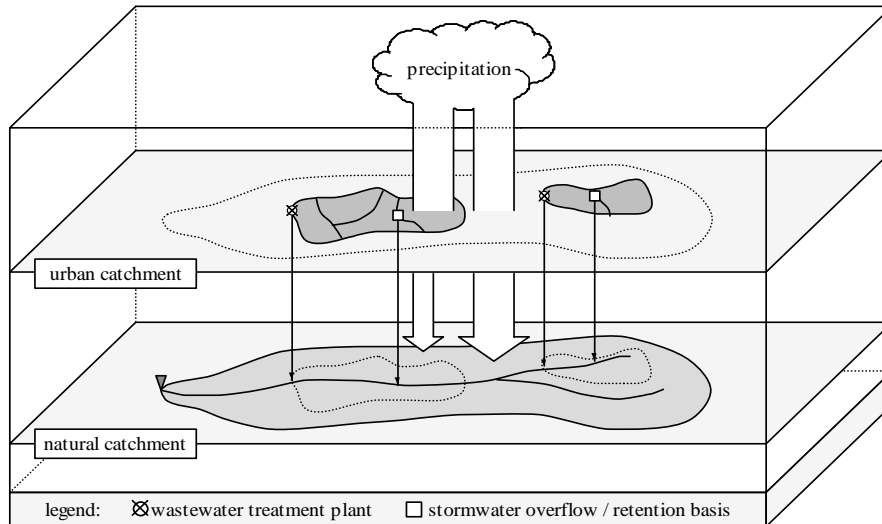


Figure 1: Visualisation of the 2-layer approach, on top the urban catchment layer, below the natural catchment layer.

The distributed deterministic grid model for rural areas is coupled with the GIS idrisi (Eastman, 1999), in which also the areal output can be displayed. An initial analysis of a digital elevation model (DEM) is the topographic basis for the model. The flow paths on the surface and the river network (Figure 2, on the left) are determined by the D8-method (O’Callaghan and Mark, 1984). The grid size is arbitrary. As further input the model requires GIS maps with information on soils and land use. The soil is regarded as a three layer system: infiltration layer, root zone and transient zone.

Canopy interception is modelled by an approach similar to the Rutter interception model. A complete routine for soil moisture accounting, based on the work of Ostrowski (1982), calculates soil moisture in all of the three soil layers, effective runoff, interflow, makropore flow, percolation into the groundwater, and capillary rise. This soil moisture accounting scheme considers backwater effects due to soil saturation and accounts for both hortonian and saturation overland flow (Lempert, 1997). Overland flow is then routed from grid to grid by the kinematic wave approach. As soon as a channel is reached on the flow path, the overland flow is routed in this channel, together with interflow and baseflow, modelled with the kinematic wave approach as well. Depending on a threshold value, up to four different channel geometries can be defined within a watershed. For both overland flow and channel flow, a non-linear reservoir approach is used to solve the kinematic wave equation.

The urban rainfall runoff and pollution load model can be categorised as a deterministic conceptual semi-distributed approach solely on hydrological concepts and features a comprehensive graphical user interface. An example of a systematic flow scheme is shown in Figure 2 on the right. Elements of

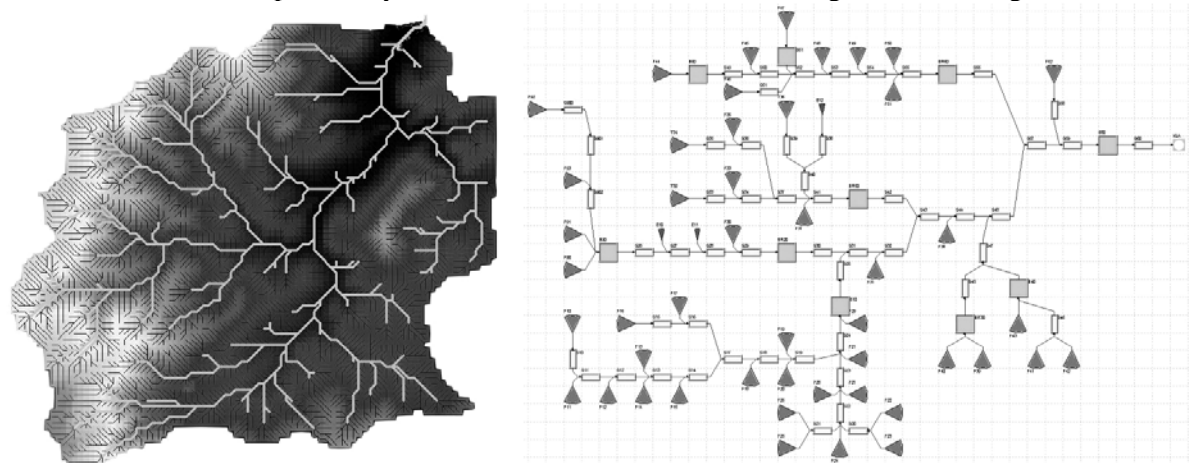


Figure 2: On the left, the structure of the grid model for rural areas is shown. Here the flow pattern, as well as the river channels according to the threshold-value concept can be seen. On the right hand side, a system flow plan of the urban model is shown. Triangles depict urban areas, small rectangles depict canals and large squares depict retention basins / overflows.

a system flow scheme are urban catchments, sewers or open channels, retention basins, stormwater overflows, discharger and wastewater treatment plants. At this stage, the urban hydrologic model already contains a module for pollution transport, which however is not further discussed in this paper.

Runoff is generated after surface wetting and a gradient dependent depression storage volume is exceeded. Runoff is then routed to the outlet by a parallel cascade of linear reservoirs, where the number of reservoirs is arbitrary. Depression storage is emptied by the potential evaporation rate after a rainstorm.

Transport in sewers and channels is based on the Kalinin-Miljukov algorithm (Kalinin and Milyukov, 2007) and computes stormwater and dry weather runoff separately. Retention basins and stormwater overflows can be modelled in several degrees of detail, and on retention basins, backwater effects can be emulated. The retention effects of up to nine wastewater treatment plants are modelled by a linear reservoir.

Precipitation is apportioned according to the degree of impermeable area in the urban catchment. Discharges from the rural areas are conveyed to the drainage system as identified by the flow path algorithm in the raster GIS. Both models aim at the adequate representation of dominant hydrological and hydraulic processes within the respective system elements, but use very different spatio-temporal resolutions. The model was applied to the River Modau Basin in the south of Hesse, where several urban areas had to be considered along the river course.

3.2 Linking an urban drainage model with the receiving water

In the second approach a fast integrated simulator was developed to facilitate multi-objective optimisation of the integrated urban wastewater system. The system consists of four subsystems, the upstream catchment, the urban sewer system, the wastewater treatment plant and the receiving water body. The same urban drainage model was used as in the first approach. This model has been coupled with a newly developed river water-quality model and a rainfall-runoff model. The water quality model is based on a modified version of the extended Streeter-Phelps model described by Chapra (1997) for the quality and a Lagrangian framework by the particle-tracking approach for the transport, the hydraulics are calculated using non-linear reservoir cascades. The used rainfall-runoff model includes soil moisture simulation based on the same non-linear model used in the first approach, relating the dominant processes infiltration, percolation and actual evapotranspiration to soil moisture. The wastewater treatment plant is simulated in a simplified way based on monitoring data. All quantitative and qualitative processes are calculated time variable on a small temporal scale (minutes).

The urban drainage model including the wastewater treatment plant was linked to the receiving water at overflow and waste water treatment plant effluent and to the upstream catchment of the urban development by defining upstream boundary flow conditions, either via time series input or by direct coupling with the rainfall runoff model. The structure of the integrated model is illustrated in figure 3; it is described in detail in Muschalla (2006a).

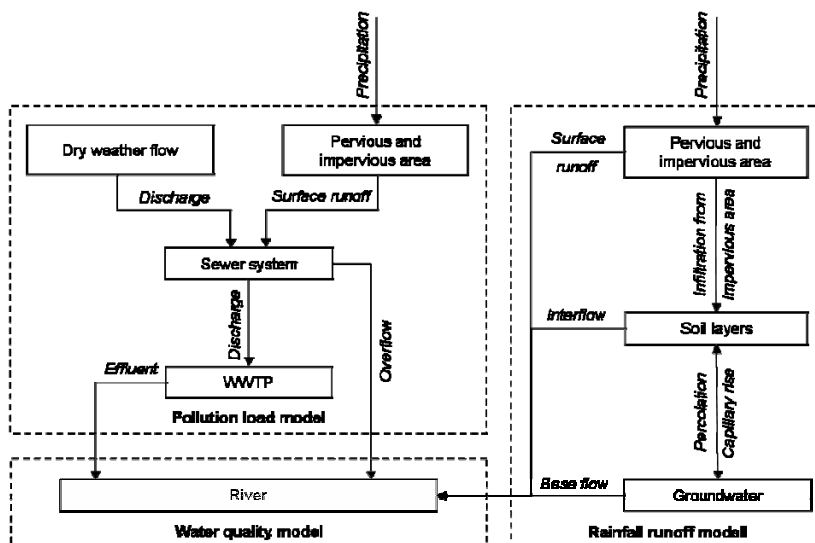


Figure 3: Structure of the integrated simulation model (Muschalla, 2006b)

3.3. SIMULATION BASED OPTIMISATION

Genetic and evolutionary algorithms have proved to be adequate approaches for many optimisation problems in water resources management. Muschalla (2006a) has recently investigated their usefulness for urban drainage problems. Due to redefined management objectives the need for algorithms is evident accounting for multi-criteria objective functions. Among derivative free search algorithms multi-objective evolutionary algorithms have become a robust and efficient optimisation method in many engineering disciplines over the last few years in general. However, only few applications can be listed in the field of urban water systems. Muschalla et al. (2007) give a survey of previous and potential applications to the multi-objective optimisation problem and evolutionary algorithms; a comprehensive literature review is included.

A new multi-objective Evolutionary Strategy was developed by Muschalla (2006a). The algorithm combines the advantages of the Non-Dominated Sorting Genetic Algorithm NSGA-II (Deb et al. 2000), the Strength Pareto Evolutionary Algorithm SPEA2 (Zitzler et al. 2001) and Self-Adaptive Evolution Strategies and contains further development improving convergence and diversity. The identification of a good spread of solutions on the Pareto-optimum front of equally acceptable optimum solutions and the optimization of a large number of decision variables equally demands numerous simulation runs. In addition, evaluation of criteria with regard to the frequency of critical concentrations in the river and peak discharges to the receiving water requires continuous long-term simulations. Therefore, a fast integrated simulation model is needed providing the required precision of the results. For this purpose, the above described integrated simulation model was developed. The integrated simulation model and the multi-objective optimization algorithm were implemented in a modular common software shell.

The developed integrated simulation and optimization system has been applied to a real urbanized catchment area (river Bieber, located nearby Frankfurt, Germany) comprising natural and urban areas, sewer system, WWTP and receiving water body. A structural optimisation and dimensioning of the urban drainage system in an integrated view considering receiving water quality impacts will be summarised later in this paper.

4. RESULTS

The combined rural-urban model was applied to the upper Modau River Basin. This basin is located in a mountainous area in its upper part before entering the River Rhine alluvial plains. It is intensively disturbed by agricultural activities and urban development. It is one of the case studies selected by the state water authorities to test different approaches for the realisation of the European Water Framework Directives. The general system structure of the basin is given in figure 4.

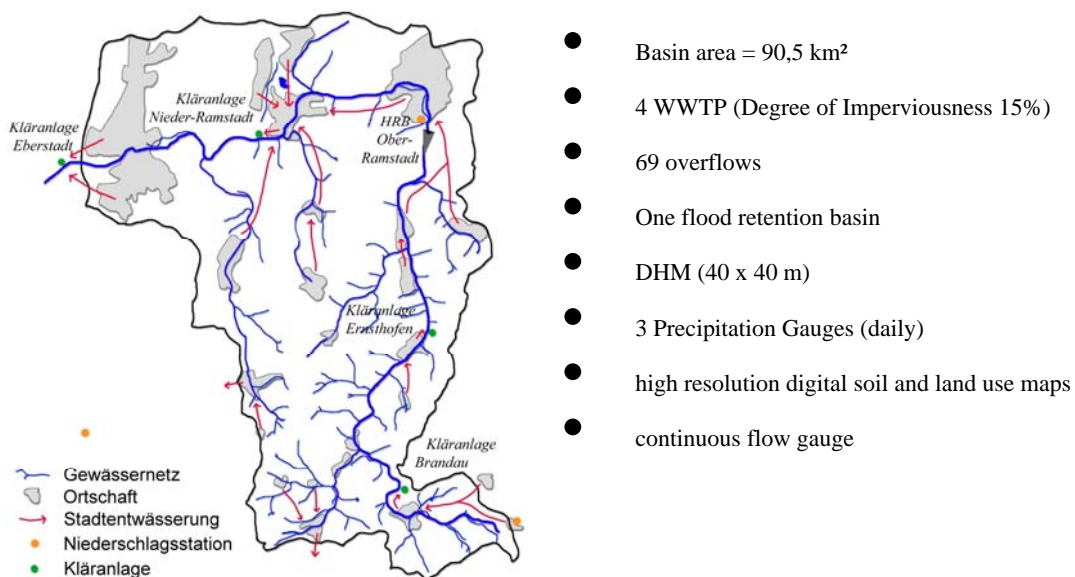


Figure 4: General Structure of the upper Modau basin

The test of the model proved that on the one hand the overall accuracy could be considerably improved as shown in Figure 5. In Figure 5a measured and computed flows were compared at the end of the catchment, which can be assessed as highly accurate. On the other hand comparisons were made concerning the differences between a model aggregating urban overflow structures and a highly resolved modelling system within the river system as shown in figure 5b. Under-estimation of the hydraulic load on the river from combined sewer overflows by 40% can occur for short events and high rainfall intensities.

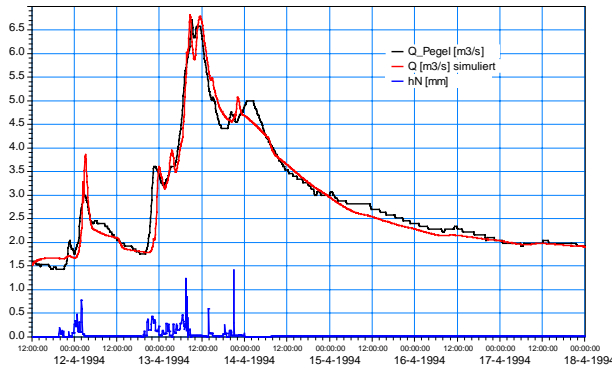


Fig. 5a: Comparison of measured and computed flow at the end of the system

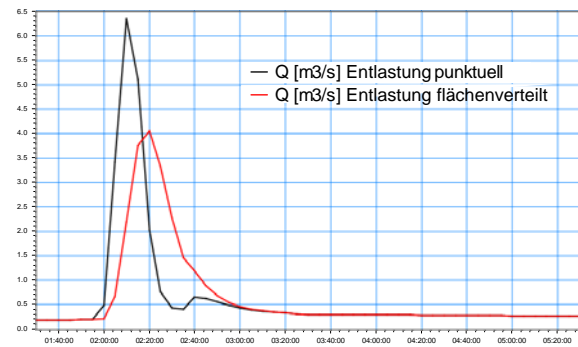


Fig. 5b: Comparison of hydrograph below urban development for aggregated and detailed simulation

The optimization and simulation tools has been tested on a real urbanized catchment area (river Bieber) consisting of impermeable sub catchments, sewer system, wastewater treatment plant, receiving water body and natural upstream river basin (total area 38 km², total urbanized area 8.8 km², urbanized area of township Heusenstamm 3.8 km², inhabitants 42,000 respectively 19,000 Heusenstamm).

The receiving water body shows significant water quality impairment and hydraulic stress during storm water overflow events. To improve the impaired status a set of optimum measures had to be chosen from a pre-selected ensemble of innovative as well as traditional measures. In this study additional in-system storage volume, decentralized infiltration, optimal adjusting of in-system throttle discharges and biological sand filters were selected as potential measures. It must be mentioned that the modelling system is able to handle only a single urban drainage system. Figure 6 shows the urban catchment area of Heusenstamm with system elements and the location of the selected measures.

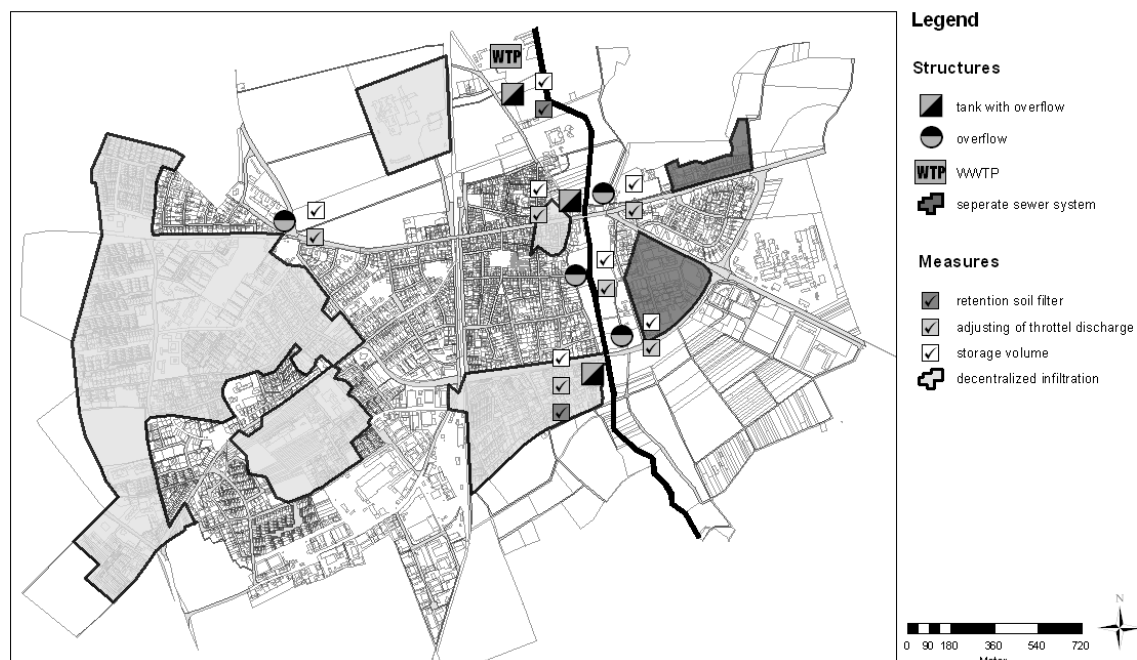


Figure 6: Examined urban catchment area with main structures and selected mitigation measures (Muschalla 2006b)

The target system combined economic objectives (minimisation of investment) with environmental quality standards (non exceedance of dissolved oxygen deficit, frequency of critical hydraulic situations in the river). The maximum allowable dissolved oxygen deficit is set to 4 mg/l. As hydraulic objective function a threshold exceedance value was defined, which is a 10 % increase of yearly maximum flow. The results of the multi-criteria analysis based on the evolutionary algorithm are given in figure 7. Each small dot represents a simulation result with the calculated maximum dissolved oxygen deficit and the maximum runoff as well as the necessary investment as value. The big dots are the non-dominated solutions representing the determined approximation of the Pareto optimum front. The light coloured marked solutions fulfil all limit values. To make the figure more clearly, the non-dominated results are projected on to the plans. The completion of the allowable maximum runoff of ~900 l/s requires a considerable amount of investment. In contrary the dissolved oxygen deficit never exceeds the allowable maximum of 4 mg/l. Anyhow a significant improvement is achievable. The minimum reachable oxygen deficit approximates the inflow deficit concentration of the upper boundary condition. It is interesting that only with a combination of different measures Pareto optimal solution could be identified which complies with all criteria.

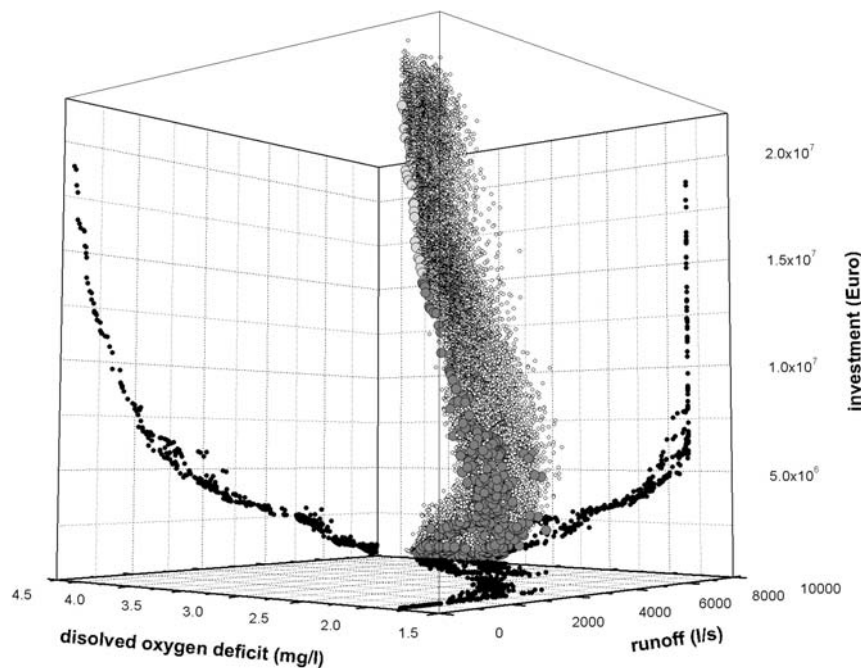


Figure 7: Results of the multi-criteria optimisation based on evolutionary algorithms

5. DISCUSSION AND CONCLUSION

The simulation models described come from two directions. The first one (top-down) started from a GIS-based basin wide raster model at high spatio-temporal resolution. Deficits due to simplified aggregated representation of urban drainage systems were overcome through a separate consideration of these systems in a second model with adequate dynamic interaction among sub-systems. The second development (bottom-up) started from an urban drainage model built for emission control which was linked to a water quality for receiving water bodies and an interface to account for dynamic upstream hydrologic conditions. At the same time this model is the basis for the identification of optimum sets of improvement measures. The overall simulation and optimisation tool box allows for the detailed hydrologic analysis of complete heavily urbanised river basins with multiple settlements as well as for the analysis of optimum improvement single urban drainage systems and adjacent receiving water bodies. Their correct functioning was demonstrated by means of case studies. The models developed largely facilitate the integrated consideration of complex river basins, however the actual situation made transparent that further integration is required.

In the next development step on the one hand the integration of the sub-models described into one modelling system is foreseen. An important additional module will be added to account for the

simulation of nutrients and pollutants from rural areas. On the other hand the integrated simulation and optimization tool box will be enhanced in such a way as to enable it to facilitate a basinwide optimisation considering multiple urban areas simultaneously. In addition, the migration of the existing model systems to OpenMI-compliant models is still in process.

It is important to notice that such complex modelling schemes are very demanding concerning input data. They will only be applied in practice if data acquisition and pre-processing will be limited to an economically acceptable level. In this case the development aims at the situation in Germany in general and the Federal State of Hesse in particular.

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