Implementation of sustainable sanitation in existing urban areas: long-term strategies for an optimised solution

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Abstract If technologies for decentralised sanitation and reuse (DESAR) and for natural stormwater management should at least partially replace existing systems, then intensive reconstruction work becomes essential. A conversion can only be realised successively over a long period due to high construction and financial expenses and requires new strategies. This paper presents the development and practical implementation of a mathematical tool to find an optimised strategy for the realisation of alternative and more decentralised drainage and sanitation concepts in existing urban areas. The succession of construction measures (e.g. the implementation of decentralised greywater recycling) for the whole period of consideration is determined based upon a mathematical optimisation model on the condition that the favoured future state is known. The model describes the complex interdependencies of the urban water and nutrient cycle and enables the minimisation of both financial efforts and ecological impacts on the way toward the future state. The results of the implementation for a rural area in Germany show that the mathematical optimisation is an adequate instrument to support decision-making processes in finding strategies for the realisation of sustainable urban water management.

Keywords Cost consideration; decentralised sanitation; mathematical modelling; optimisation of strategies; sustainable urban water management

Background

The present dominance of centralised concepts for urban drainage and water supply in developed countries unquestionably does not comply with sustainable requirements. Alternative concepts of sustainable drainage (sustainable urban drainage systems - SUDS) and decentralised sanitation and reuse (DESAR) have become more and more significant in recent years (e.g. Lens *et al.*, 2001). If technologies for closing urban water and nutrient cycles should at least partially replace existing centralised end-of-pipe systems, intensive reconstruction work becomes essential. The realisation of advanced sanitation concepts in existing areas would cause extensive financial and construction efforts and would be more difficult – particularly because of residents' acceptance – than the implementation of sustainable stormwater management. Decision support approaches to the selection of sustainable drainage systems or DESAR concepts are investigated in some studies (e.g. Huang *et al.*, 2004; Ellis *et al.*, 2006). Finding strategies to reach a more sustainable future state in an optimal way has not been investigated so far. At all stages of transition a reliable water supply and disposal of wastewater have to be guaranteed. A conversion can only be realised successively over a long period of time due to high construction and financial expenses, and requires new strategies for "hot plug-in". Manually such an optimal strategy to attain the favoured future state cannot really be found. Therefore, an urgent need for research exists to find optimised strategies

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for implementation of decentralised and sustainable drainage and sanitation devices in existing urban areas on conditions that the favoured future state is known. This paper will present the development and application of a mathematical optimisation tool to determine the succession of the construction of devices under minimal ecological impacts and economic efforts.

Advanced sanitation in the context of the optimisation model

For the optimisation model, three different categories of measures for the transition from the present state to the favoured future state are considered: devices for a natural rainwater management (SUDS), devices for advanced sanitation (greywater and blackwater treatment and reuse) and sewer and surface drainage (re)construction. In this paper only measures for the implementation of decentralised sanitation and reuse are briefly described in respect to the mathematical optimisation model where only "standard" concepts are used. As in the mathematical tool so far the influence of treatment processes in central wastewater treatment plants (WWTP) is not considered, only impacts on drainage systems and receiving waters are mentioned.

Decentralised greywater treatment

Domestic wastewater from bathrooms and kitchens (greywater) can be treated with relatively low effort to render the recycled water fit for the specific reuse purpose. As greywater production is constant and exceeds the demand of water for non-potable applications (flushing water, garden watering or washing clothes) greywater recycling is adequate for all kinds of settlements. In Germany the best available technology for greywater recycling was introduced by a regulation of the professional association "fbr" (2005). Storage tanks as well as technical biological treatment plants using membrane, contactor or fluidised bed concepts require little space for installation. Compact systems are offered by various providers for different utilisation qualities with prices of 3,500 € to 7,000 €. However, in buildings without basements it is difficult to find an appropriate place to put these systems, as the location must be accessible for maintenance work. For natural treatment, soil filters require $1-2\,m^2$ per inhabitant. Retrofitting systems to individual houses requires a double collection and distribution pipe network, which can be expensive (ca. 2,000 € for two-storey houses (BMLFUW, 2005)). The devices for decentralised greywater management used for the optimisation model are shown with their costs and installation periods later in this paper.

Domestic greywater recycling reduces the need for potable water (up to 50%) and thus relieves the demand on public water supplies and wastewater collection and treatment facilities. For the mathematical modelling, present and resulting effluents and pollution loads per inhabitant are calculated. Owing to declining flow velocities, sedimentation or corrosion in sewers can increase and necessitate frequent sewer cleaning. In the model the flow velocity is checked and at very low velocities higher sewer flushing costs are calculated. If a minimum velocity is not ensured, the sewer has to be reconstructed or replaced by another transport system (e.g. pressurised or vacuum systems). The remaining effluent part of foul water shows a considerably higher concentration of nutrients. In combined sewer systems, concentrations in combined sewer overflows (CSOs) can increase.

Decentralised treatment of faeces and urine

In addition to reuse greywater for non-potable applications, a recycling of nutrients contained in faeces and urine (blackwater) can be realised by different approaches. To isolate and reuse urine as fertiliser, special no-mix toilets are required. In principle, the application of no-mix toilets in houses is possible. As mentioned above, especially in buildings with "distributed" bathrooms, retrofitting is cost- and labour-intensive. In this paper only on-site storage and collection are considered. A storage volume of 2.5 L/(inh. and day) for a storage time of about 6 months is necessary. A limiting factor in reusing urine as fertilizer is the demand of nearby agriculture, as transport is only cost-effective up to 200 km (BMLFUW, 2005).

Composting faeces (and urine) can be realised by individual compost toilets or by large systems for a whole house. The latter are not really feasible in existing houses due to the required space and layout of house drainage (one vertical stack is needed). Composting systems have to be maintained intensively and are suitable if land for manure is available.

For (semi)decentralised biological treatment of faeces (and urine), at present anaerobic techniques are applied. Resulting biogas can be used on-site and the remaining liquid fertiliser can be directly utilised in agriculture. Biogas plants are realisable for the connection of more than 100 inhabitants. The supplementary installation in existing areas causes high efforts for drainage elements and technical plants as well as space requirement (ca. 2,000 €/inh.).

Urine separation has almost no effect on wastewater quantity in existing centralised systems at an absence of around 70% of nitrogen in wastewater. If the whole blackwater fraction is treated in a decentralised setting, one-third of domestic wastewater is retained from sewer systems and WWTPs. If volume and pollution of dry weather flow are reduced, in combined sewer systems CSO discharges and loads will be reduced. The altered wastewater composition can negatively, as well as positively, influence treatment processes at the WWTP.

For measures in the decentralised sanitation sector the following dates were estimated as listed in Table 1. For complex reasons greywater is not split into wastewater from bathrooms and kitchens.

Mathematical approach

The optimisation tool has been developed to find an optimised strategy to reach a favoured future state. The more sustainable specifications for drainage and wastewater treatment for the future are not determined by the tool. The condition for the application of the model is to know what general objectives (such as extensive decentralised greywater recycling) should be reached in the future.

Design of the model

The progression within the optimising procedure was defined as shown in Figure 1. The mathematical modelling is based upon the scale of subcatchments and simplified networks of drainage elements (functioning network). All subcatchments are connected due to flow directions and all interrelationships of the main elements are represented. This allows, besides the temporal succession of appropriate measures, a spatial consideration.

Based upon the boundary conditions of the present state and the favoured future state, potentially realisable measures are provided for each subcatchment (depending on numerous parameters, e.g. topography, subsurface conditions, land use, space requirements and population density). For all measures, investment costs and operating costs as well as installation periods are calculated in all subcatchments. Furthermore, information about impacts on flows, discharge and pollution are linked to each measure allowing a simplified balancing of volumes and loads in different flow types and discharge paths (e.g. waterbodies, WWTP effluent, soil). The environmental impact is estimated by ecological costs expressing negative as well as positive ecological impacts. Within the optimising

Table 1 Measures for grey- and blackwater treatment as used in the mathematical optimisation model (based on the literature and internet survey)

Measure/device	Wastewater component				Investment costs	Operational costs	Installation period	Useful lifespan
	Greywater	Flushing Water	Urine	Faeces	€/inh.	€/(inh. year)	Man-day/inh	Years
Direct reduction of water consumption for greywater	+	−	−	−	25	0	0.25	25
Direct reduction of water consumption for blackwater	−	+	−	−	50	0	0.25	25
Greywater treatment (and reuse) by technical devices	+	−	−	−	1,600(1,800)	8(10)	10	35
Greywater treatment (and reuse) by natural devices	+	−	−	−	800(1,000)	12(14)	10	25
Centralised treatment of greywater at WWTP*	+	−	−	−	0	0	1	–
Compost toilets with individual seats/with larger house installation	−	+	+	+	1,800/1,200	20/15	5	25
Decentralised biological blackwater treatment	−	+	+	+	2,000	10	5	35
Separation of urine and on-site storage	−	−	+***	−	500	120	3	25
Centralised treatment of blackwater at WWTP**	−	+	+	+	0	0	1	–
Small sewage treatment plants	+	+	+	+	1,250	50	7	30

+, applicable for component; −, not applicable for component; +, components have to be treated combined
*The measure has to be implemented for the whole catchment (simplification). Blackwater must not be connected to centralised sewers. Costs for retrofitting of house drainage are included in devices for blackwater
**The measure has to be implemented for the whole catchment (simplification). Greywater must not be connected to centralised sewers
***Flushing water is neglected

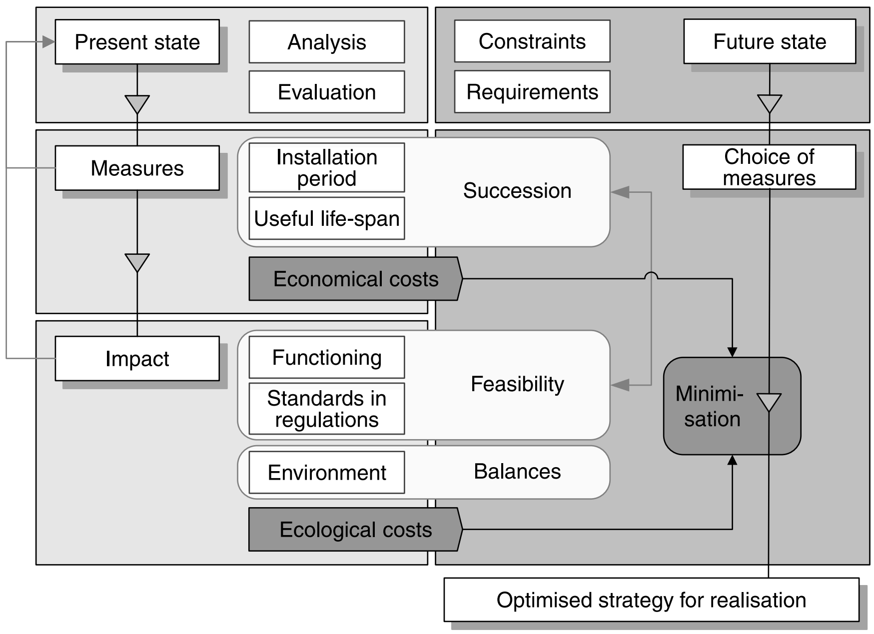

Figure 1 Scheme of mathematical optimisation model

process the feasibility of the systems is verified in each time step, which decisively affects the succession of conversation measures. The requirements of the favoured future state expedient measures are chosen in such a way that on the one hand, the hydraulic and legally allowed functioning of the systems is ensured at any time; on the other hand, the succession of measures should cause the minimal economic and ecological costs.

Financial efforts (economic costs) as well as ecological impacts (ecological costs) should be minimised on the way to more sustainable systems. Therefore the problem mentioned belongs to the field of multi-criteria optimisation. Such feasible strategies of conversion should be found, which could not be enhanced in both criteria. Generally, not only one solution of the optimisation problem exists but numerous reasonable Pareto-optimal solutions (see e.g. Ehrgott, 2005). Only the subjective weighting of the different criteria or the discussion of local decision makers can lead to the definite choice of the optimised strategy for realisation.

Mathematical modelling

The structure of the mathematical model was built as a complex network of nodes and arcs, the possible connection between nodes. Figure 2 demonstrates the complexity of the node–arc–network starting from one wastewater component. For instance, the waste water component greywater is linked to the possible greywater treatment devices with and without reuse, respectively, or drainage elements. If greywater has been treated it can be connected not only to foul or combined sewers but also to (stormwater) drainage systems to be discharged into receiving waters. Furthermore, an infiltration of purified greywater is possible. For balancing reasons the nodes' treatment (for "retained" pollution), reuse (rate of treated greywater to be used in households), infiltration (possibly infiltrated rate) and evaporation (evaporated rate from natural treatment devices or infiltration swales) are necessary. Starting from one foul water component apparently numerous arcs are necessary to describe the complex interdependencies between water cycle, transport elements and pollution paths. The node–arc network can easily reach dimensions of about 100 nodes and 300 arcs for each subcatchment.

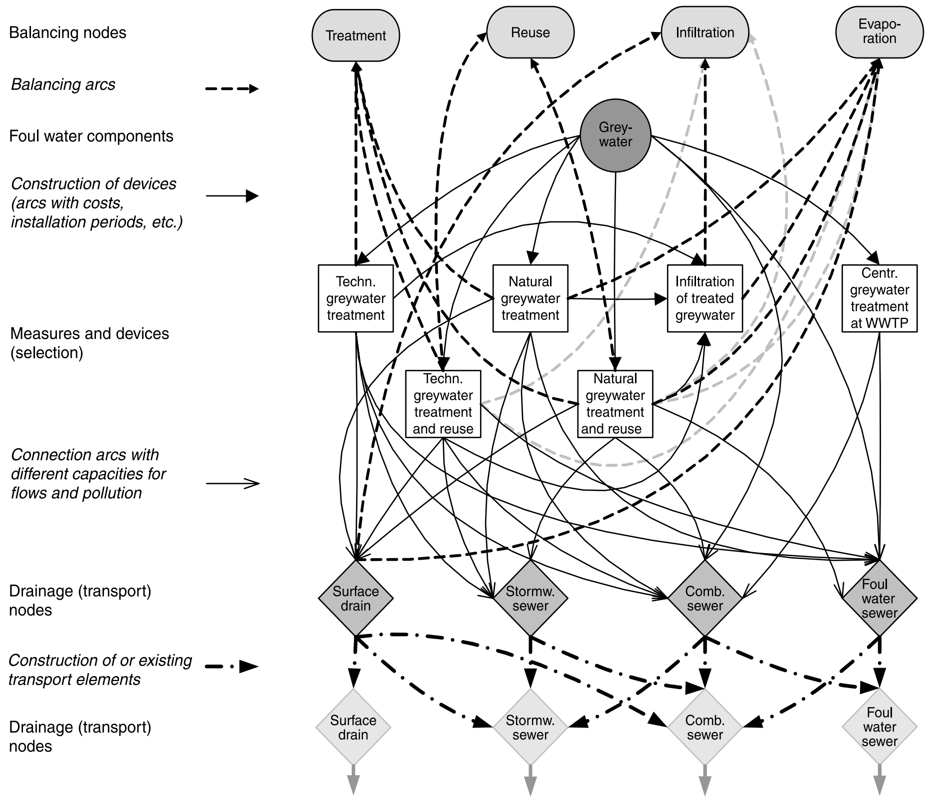

Figure 2 Model structure of nodes and arcs starting from one wastewater component in a subcatchment

Based on this structure, a simultaneous project scheduling and network flow problem is defined and formulated as a bi-criteria mixed-integer programme (MIP). The challenge and specifics are, on the one hand, that not all specified expedient measures have to be chosen but just those measures should be selected, which lead to a Pareto-optimal strategy. On the other hand, the network for the scheduling and flow problem is time dependent, as with the construction of different devices, arcs are opened due to installation periods and closed when elements are replaced by new devices.

By the implementation of different variables and adequate constraints within the mathematical modelling procedure all paths of the network are scant in order to find a feasible optimal solution under the consideration of economic and ecological costs, the objective functions of the model.

At every time step the economical costs are calculated primarily as the sum of:

- investment costs (€) of devices with beginning of construction in the regarded time step;
- operating costs (€/year) of all installed measures;
- rehabilitation and reinvestment costs respectively (€).

Economic costs are calculated as total project costs with a real estate rate of 3% for the whole period under consideration. The real estate rate can be varied as well as budget limits for time periods can be defined if required.

The ecological costs are not accounted monetarily but by a point system. Positive points represent an environmental “damage” whereas negative numbers express a benefit. The costs are calculated on-line by simplified methods. The different criteria (e.g. distance from natural water cycle, distance from favoured resources protection or emitted pollution loads in water bodies) can be weighted individually. Further information on the mathematical model is given in Kaufmann *et al.* (2006, 2007).

Implementation of the model

Catchment and boundary conditions

The model has been implemented for a suburb of Kaiserslautern in Germany, a rural catchment of about 3,000 inhabitants. The entire catchment has a drainage area of about 90 ha and includes 35 ha of paved area. About 30% is drained by (modified) separate systems whereas the rest consists of combined sewer systems. Two combined sewer overflow devices and one final sewer overflow tank are installed in the sewer system. A business park in the south of the suburb has an area of about 20 ha and its effluent shows the characteristics of domestic wastewater. Dry weather flow amounts to 11.5 L/s and consists of 6.0 L/s foul sewage, 2.0 L/s industrial sewage and 3.5 L/s infiltration water. The pollution of dry weather flow is 560 mg COD/L. Within the optimisation model (so far) only the parameter COD (chemical oxygen demand) is implemented. In a detailed preprocessing 32 subcatchments from 1 ha to 20 ha area were determined based upon land use factors, population density, geological boundary conditions and sewer or surficial flow directions. For all subcatchments, potentially realisable measures are assessed using an own decision support tool.

In this paper two extreme scenarios characterised by requirements listed in Table 2 are chosen as examples of numerous potential future states. In this example, in scenario 2, greywater from bathrooms, washing machines and kitchens should be used for recycling and reused for toilet flushing, cleaning purposes and laundry.

The above explained economic and ecological costs are weighted equally. This means that such an optimal strategy has to be found where both costs are minimised concurrently for the period of consideration (minimal financial efforts for the lowest ecological impacts). For the realisation of the future state a period of 55 years was considered.

Results and discussion

For the specific conditions and for one subcatchment (characterised by residential areas) the succession of construction measures for the optimised strategy is shown in Figure 3. The beginning of construction as well as installation periods and phases of rehabilitation are shown for the two scenarios. For more natural stormwater management the same devices are implemented in S 1 and S 2. In S 1 rainwater from roofs is used in households as well as for garden watering. In S 2 collected rainwater is only used for garden watering as greywater is reused in households. In both scenarios the existing combined sewer is used to discharge resulting stormwater runoff and for the foul water components

Table 2 Characteristics of scenarios

Scenarios		Stormwater	Greywater	Blackwater
S 1	Decentralised treatment of blackwater	- Stormwater runoff and wastewater should not be mixed any more	Should be treated centrally at WWTP	Completely decentralised treatment
S 2	Decentralised treatment of greywater	- More natural stormwater management	Extensive decentralised recycling and reuse	Should be treated centrally at WWTP

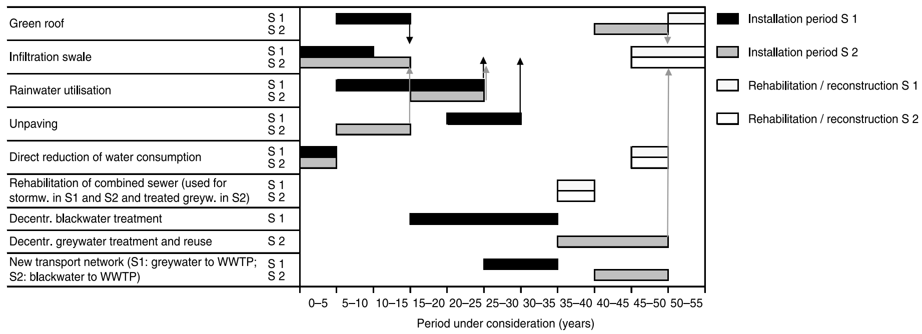

Figure 3 Succession of measures for a subcatchment as the result of mathematical modelling

a new transport system is built. In S 2 treated greywater, which is not reused, is either infiltrated or directed to the stormwater sewer (former combined sewer).

In this example the implementation of S 1 (decentralised blackwater treatment) is more expensive than the implementation of S 2 (decentralised greywater treatment). All in all, in S 1 31.8 million € result as the total project costs and in S 2 26.8 million €. These economic costs are the sum of the installation costs and operational costs of the activities chosen by the model, accounted with an interest rate of 3%. The model produces such an optimal strategy for the implementation of the different measures, that the costs (in the example the economical and ecological costs concurrently) are minimal. At this, it has to be mentioned that in the present version of the optimisation tool neither are economic costs split into private and public costs nor are savings, e.g. for reduction in water consumption, considered.

As example of impacts on existing systems, the effects on dry weather flow in centralised systems of the considered suburb are shown in Figure 4. The changes in treatment of foul water as well as the resulting COD concentrations in foul and dry weather flow are demonstrated. In both scenarios about 40% of the need for potable water is directly reduced by the application of new taps and fittings. In S 2 more than 20% of the water consumption of the present state is additionally replaced by recycled greywater. The resulting concentration of COD in the foul water flow changes greatly in S 2, in which the whole greywater component is separated from centralised systems. The concentration in foul water at the inflow to WWTP rises from 800 mg/L in the present state to almost 2,400 mg/L in the future state. In the whole dry weather flow it changes from 560 to 710 mg/L. In S 1 dry weather concentration is reduced to 440 mg/L in the future state. These changes influence for instance the overflow loads of COD at the combined sewer overflow devices. In S 1, in the 55 years of consideration, 160 tons are emitted whereas in S 2,240 tons are discharged at CSOs. In both scenarios the emitted volumes and loads are reduced in comparison with the present state. If no measures were implemented, in the 55 years 460 tons of COD would have been emitted via CSOs.

Conclusion and outlook

Numerous alternatives for stormwater drainage and the reuse of domestic wastewater (non-potable applications and nutrient recycling) have been established in recent years. The present change in exposure to wastewater would cause intensive reconstruction work for existing centralised drainage systems if discussed sustainable objectives are to be achieved. To ensure that every step of reconstruction ecologically and economically benefits the future, an optimised strategy for the transition of systems should be investigated. A first tool to find such strategies, under the condition that the favoured future state is

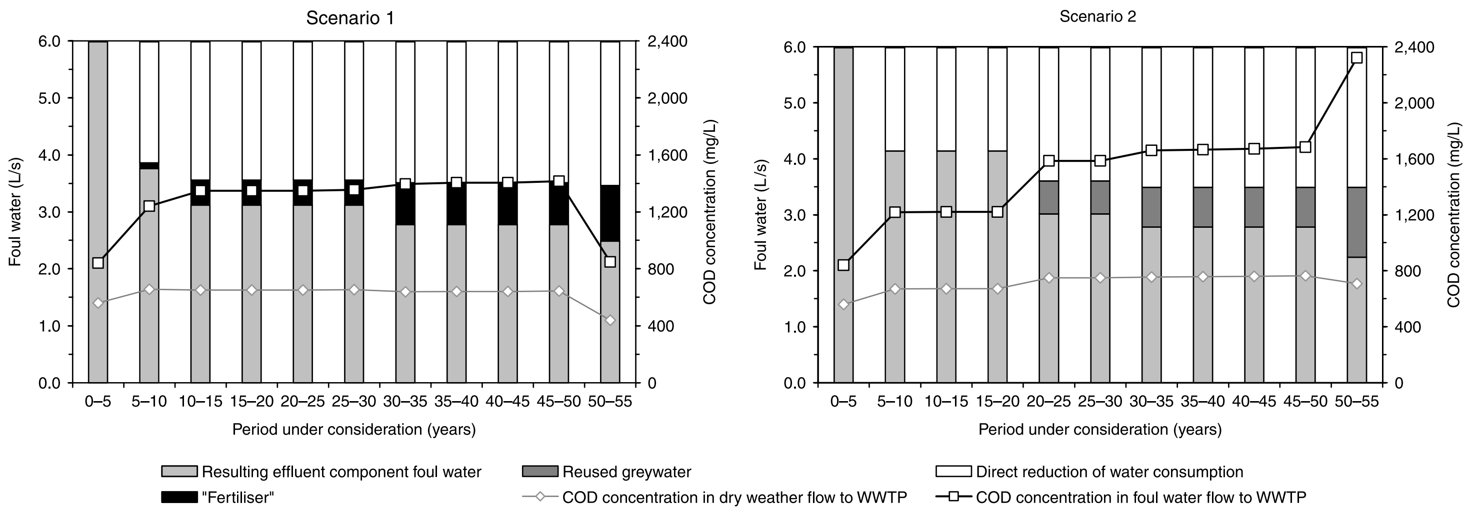

Figure 4 Temporal changes in foulwater treatment for the two scenarios

known, was developed as a bi-criteria optimisation model and implemented for a rural area in Germany. The mathematical approach necessitates many simplifications due to the high complexity of interdependencies in the urban water and nutrient cycle. Nevertheless, the results are plausible and optimal strategies for the sequence of measures to more sustainable systems under ecological and economical aspects can be found.

More reliable strategies could be developed if many more constraints, for instance the detailed consideration of wastewater treatment processes and receiving water or population development, are taken into account. The hitherto investigations have also shown that current guidelines and regulations could increase the price of or even inhibit favoured retrofitting of drainage systems. In the meantime, there will result states where not all regulations can be fulfilled. Therefore, standards should be adapted to changing systems. Furthermore it is essential to define the requirements and conditions of favoured future states, such as an obligatory rate of greywater reuse, fertiliser production or admissible emissions. They also have an important influence on costs and impacts of reconstruction measures.

The mathematical optimisation has proved to be an adequate instrument to find strategies for the realisation of sustainable urban water management. The developed tool possibly will be a support for decision-making processes. The potential of the approach will increase with the complexity of the specific application. For complex systems an optimal solution for transition to a favoured future state cannot be found manually.

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