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Research article

A combined model to assess technical and economic consequences of changing conditions and management options for wastewater utilities

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ABSTRACT

The paper presents a simplified model that quantifies economic and technical consequences of changing conditions in wastewater systems on utility level. It has been developed based on data from stakeholders and ministries, collected by a survey that determined resulting effects and adapted measures. The model comprises all substantial cost relevant assets and activities of a typical German wastewater utility. It consists of three modules: i) *Sewer* for describing the state development of sewer systems, ii) *WWTP* for process parameter consideration of waste water treatment plants (WWTP) and iii) *Cost Accounting* for calculation of expenses in the cost categories and resulting charges. Validity and accuracy of this model was verified by using historical data from an exemplary wastewater utility. Calculated process as well as economic parameters shows a high accuracy compared to measured parameters and given expenses. Thus, the model is proposed to support strategic, process oriented decision making on utility level.

1. Introduction

In contrast to the global trend many regions in Europe suffer from a decrease and aging of population, often described as "demographic change". In parallel, legal, technical and economic conditions are changing with integrally acting consequences for utilities. Assessment of the effects and development of appropriate adaptation measures demand for approaches which are able to describe the causal and complex relationships between changing conditions, technical system and economic effects.

The shrinking population, high fix costs and long depreciation periods create economic but also technical challenges. To adapt timely and sustainable, it is important to quantitatively predict technical and economic effects of those changes and to evaluate the effectiveness of subsequent measures. There exist a lot of valuable programs for simulating processes of WWTP, sewer system as well the aquatic environment with which the effects of changing conditions can be considered. These programs are generally focused on certain systems and questions (like hydrodynamic sewer models, rehabilitation models, activated sludge models etc.). Generally, they are complex and require a high data density and thorough parameterization. Even cost management models for efficiency analysis and decision support tools provide no holistic approach to reflect the cost of utility administration, sewer and treatment plants. Different approaches for both sectors are presented in literature. For sewer maintenance cost, a dynamic systems model developed by Rehan et al. (2014) to support the development of financially sustainable management strategies. Hernandez-Sancho et al. (2011) developed a cost modeling methodology for wastewater treatment processes based on statistical information by aiming at a better understanding of the cost structure of wastewater treatment processes. Also based on data envelopment analysis (DEA) Castellet and Molinios-Senante (2016) developed a non-radial approach by integrating technical, economic and environmental issues for efficiency evaluation of WWTPs. Ruiz-Rosa et al. (2016) designed and adapted a cost management model to calculate the costs of each activity involved in wastewater treatment and reuse processes by combining DEA and Life Cycle Assessment (LCA) indicators. On utility level, models exist to estimate the performance and efficiency. One example is the DEA model by Ferreira da Cruz et al. (2013) which measures separately the efficiency of each service. In combination with other indicators, this model can be used for prioritizing efforts to improve overall efficiency. An intra-utility performance management model was proposed by Haider et al. (2016) as a decision tool for sustainability assessment of small and medium sized water utilities.

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An integrated technical and economic planning, especially if changing boundary conditions are regarded, a process-oriented approach is required. This has to combine models, which realistically can describe the causal relationships within the actual technical system with an economic assessment tool, reflecting the cost structure of the respective utility.

A rather pragmatic approach for such a combined assessment has been proposed by the DWA-Workgroup WI-1.3 and illustrated for a defined "standard water utility". This method based on a simplified simulation that uses corporate benchmarking indicators. For selected trends, the economic effects of and their superposition can be derived. The model serves to generalize economic effects on changing conditions in the water sector, but depends on the availability of utility specific benchmarking data. The relationships between changing boundary conditions, infrastructure, and economic effects are rather conceptual. Complex interactions or e.g. changes in organizational structures and far going changes of the technical system cannot be adequately reflected (Tränckner et al., 2014).

To achieve a balance between limited data availability and expressiveness a process oriented but still sufficiently simple model was developed. This paper presents

- The structure of the simplified process-based and economic model focused on publicly available infrastructure data, WWTPs data and expenses of the utilities.
- The validation of the model based on historical data of an exemplary utility in Mecklenburg-Vorpommern, Germany.
- An exemplary quantitative forecast of technical and economic effects till 2050 due to assumed future changes.

The following sections describe the model development and its structure as well as its components (modules) and input parameters. Based on data from an exemplary utility, the model is tested, validated and the results and accuracy are discussed.

2. Model development and structure

The model is programmed in MATLAB®, a commercial numerical computing environment provided by MathWorks®. It comprises substantial cost relevant assets and activities of a typical German wastewater utility limited to the core tasks wastewater disposal and treatment. It is subdivided into three modules (see Fig. 1). The module *Sewer* is a simplified asset management tool of the sewer system, modeling the condition as function of aging and defined activities for repair/renovation/renewal. The module *WWTP* is a process oriented tool calculating inflow and outflow parameters of the actual specific WWTP as well as cost relevant technical parameters. All necessary parameters from the module *Sewer* and *WWTP* are used in economic assessment module *Cost Accounting*.

2.1. Data set

In order to specifically address the different structural, operational and administrative conditions of a specific utility, the model demands a rather comprehensive data set. In the phase of model development, data collection was rather challenging due to the data's sensitivity and the required time-consuming preparation. Therefore, previously collected data provided by statistical institutes and ministries were accessed. Table 1 gives an overview of the collected data and their origins.

The data of statistical institutes and ministries were taken at municipality level. The service area of a utility often differs from the official administrative borders. This required structured and reproducible approaches to compare process and assign the actual service area to available data. For the case study, the data and their interrelations were double-checked for accuracy and plausibility by the stakeholder. In addition, individual surveys were conducted to obtain stakeholder data.

2.2. Module sewer

The module *Sewer* describes the development of sewage systems state due to aging and subsequent rehabilitations measures. Input parameters for the module sewer are i) the classification of the sewer network into age groups (<10a, >10a, >20a, >30a, >40a, >50a) and ii) condition states (CS) according to DWA-M149-3 (2015) from CS 5 (best condition, meaning new sewers with no defects) to CS 0 (worst condition, meaning old sewers at the end of their life cycle with many or great defects). Calculation of age groups, determines the end of depreciation from network parts. Due to structural deterioration, the sewage system does not develop linearly, rehabilitation may be necessary at earlier stages. Therefore, CS are estimated to determine which parts of the sewer network need rehabilitation.

The sewer system is rehabilitated according to age and condition, beginning with the oldest age group and worst CS and ending with the younger age groups and better CS. The rehabilitations and developments are calculated in annual time steps for the cost calculation while transitions between age groups occur in ten years intervals. For transition of CS, the cohort survival function from Herz (1996) is used. This function, called the Herz-distribution, calculates the annual percentage of sewer parts which stay in the same CS (cohort). The parameters of the survival functions, including the aging vector, the transition vector and the resistance vector, were calibrated according to Jansen (2007), who describes the calibration for the program AQUA-WertMin. The parameters can be adjusted to the specific sewer system. This approach is also integrated in other software products like DynaStrat and KANEW-Z, which are mainly proposed by German consulting offices (Kley and Caradot, 2013).

In context of long term strategies and budget requirements, the cohort survival approach is very useful and is simple to compute (Ana and Bauwens, 2010; Kley and Caradot, 2013). However, the Herz-functions seem to overestimate the actual survival rates and remaining life expectancies (Le Gat, 2008). Beside the statistical deterioration approach from Herz, there are countless different deterioration models which could alternatively implemented. Several review papers give a good overview of the available models. Yang (2004) categorized the model types into three classes: physical models, artificial intelligence based models (e.g neural network, Fuzzy set theory), and statistical models. Rajani and Kleiner (2001) give an overview and description of physical models. They subdivided them into probabilistic and deterministic models. The companion paper of Kleiner and Rajani (2001) focuses on statistical models and divide this class into deterministic models with a subdivision in time exponential models and time linear models as well as probabilistic models with the subdivision in multi-variate models (proportional hazards models, accelerated lifetime models, time-dependent poisson models) and single-variate group-processing models (cohort survival model, Bayesian diagnostic model, semi-markov model, break clustering). Ana and Bauwens (2010) subdivide the statistical models generally into two groups: pipe group models to predict the condition of a sewer group (cohorts) and pipe level models to simulate each single pipe. For all groups different models were presented and described in the paper. Because of the data set in this study, only statistical sewer group models can be used. Models to simulate individual pipes need a more detailed data set.