Trajectory of Sewerage System Development Optimization

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Abstract. The transition to market relations has determined a new technology for our country to manage the development of urban engineering systems. This technology has shifted to the municipal level and it can, in large, be presented in two stages. The first is the development of a scheme for the development of the water supply and sanitation system, the second is the implementation of this scheme on the basis of investment programs of utilities. In the investment programs, financial support is provided for the development and reconstruction of water disposal systems due to the investment component in the tariff, connection fees for newly commissioned capital construction projects and targeted financing for selected state and municipal programs, loans and credits. Financial provision with the development of sewerage systems becomes limited and the problem arises in their rational distribution between the construction of new water disposal facilities and the reconstruction of existing ones. The paper suggests a methodology for developing options for the development of sewerage systems, selecting the best of them by the life cycle cost criterion, taking into account the limited investments in their construction, models and methods of analysis, optimizing their reconstruction and development, taking into account reliability and seismic resistance.

1. Introduction

In our country the existing sewerage systems in cities and industrial enterprises do not fully correspond to modern technological, ecological and sanitary requirements, set out in the respective requirements, technological regulations and standards. The reason was the protracted transition of municipal systems into the market relations. This transition, in our view, is still ongoing and it is difficult to say when it will be completed. Nevertheless, it brought many new ways in management and work organization, new technologies in exploitation and equipment. However, there were problems with the restoration of worn-out networks and facilities (depreciation of 60-80%), increase of accident, some sections and facilities began to work in overloaded modes, while others actually do not work. Urgent measures are required to intensify, reconstruct and develop sewerage systems. It also requires improvement of development management system and its adaptation to market mechanisms.

Obviously, the process of development management of engineering systems should be permanent, continuous, adaptive and with financial security. This process can be represented as a sequential and iterative solution of two problems:

- Work intensification of existing networks and facilities;
- Reconstruction and expansion of existing facilities and construction of new ones.
Task of intensification consists:

- In carrying out of preventive measures aimed at increasing the bandwidth of networks and facilities;
- In the identification of "narrow" places and their elimination by replacements (strengthening) of some existing network elements;
- In the choice of rational modes of operation of pumping stations, treatment plants, storage tanks, pressure and gravity sewers;
- In the optimization of modes and setting up networks, zoning and redistribution of flows, etc.

It should be noted that the intensification of sewerage systems would be effective if they have inner reserves for network bandwidth, the productivity of pumping stations, pressure and gravity sewers. However, these reserves with the growing of load, the emergence of new consumers are being reduced. It can happen that reserves will not be enough for the wastewater collection, transportation. In this case, reconstruction, expansion and development of existing networks and facilities would be required. This problem is quite complex and consists of:

- The determining of structure and parameters of the new elements of the sewerage system;
- The choice of rational methods for reconstruction and optimization of parameters of the reconstructed pressure and gravity pipelines and structures;
- Development of measures to ensure the required reliability, environmental safety, and control of individual structures and sewerage systems in general.

Obviously, when solving these problems, the possible reserve of bandwidth of network and facilities need to be identified. This reserve can be provided through overstatement of design loads, parameters of sections, pumping stations, etc., or through priority construction paces (in comparison with the installation of the wastewater facilities) the pace of construction. If the reserve will be small, the whole process of development management will be in the constant reconstruction of network and facility elements. If it is large, it can lead to great "necrosis" of capital investments and the sewerage system will be in the non-rational modes of operation (siltling, clogging of network sections).

Therefore, there is a problem of choosing the optimal reserve and distribution of investment in the development of new and reconstruction of existing network and facility elements by years and developmental periods of sewerage systems. The problem is complex, many-sided and includes:

- The cost-effectiveness evaluation of steps and reconstruction stages and development of sewerage systems;
- Feasibility study on the parameters of developing sewerage systems;
- Technical and financial feasibility of the options for sewerage systems development.

The emergence and development of new technologies and materials, including different ways of trenchless pipe laying, repair and reconstruction of existing and new pipelines \([1,2]\), significantly contribute to the rapid and planned restoration of worn-out networks and facilities.

In many European cities, pipeline open pit installation has been already banned. With the development of built-up areas, the variance of pipeline tracing and methods of reconstruction are significantly reduced.

In this case, method of redundant design schemes is an efficient approach that are formed by applying in advance alternatives options of laying sewers, reconstruction, and development of sewerage systems \([3]\). Application of the redundant design schemes method allows to avoid non-optimal solutions and provides an opportunity to generate a lot of feasible options for the structures and parameters of sewerage systems, differing on costs of labor and material resources. In drawing up the redundant scheme, we can in advance designate the possible ways of section's reconstruction (parallel laying, pipeline relining, construction of a new sewer, set up pumping stations, etc...). Consequently, models and techniques that are in the investigation of sewerage system's parameters must ensure that inefficient (relative to the selected optimization criterion) pipe sections, diameters, pumping stations, pressure and gravity sewers, sewage treatment plants would be removed.
2. Materials and methods

As noted, sewerage systems development is going on stage-by-stage, capital investments are carried out discretely and at different times, while operating costs are being decreased or increased. For water supply and sewerage systems, the methodological guidelines [4] recommends to carry out an options comparison by the criterion of the reduced costs.

Subject to the priority of construction and putting into operation of sewerage systems, this criterion takes the following form:

$$Z_v = \sum_{v=1}^{V} \left( K_v \cdot \left(1 + E \right)^{\tau - \theta (v-1)} + I_v \cdot \left[ \left(1 + E \right)^\theta - 1 \right] \right) + I_n \cdot \frac{\left(1 + E \right)^{\tau - \theta}}{E}$$

(1)

where:
- $v = 1, ..., V$ - index and the number of steps;
- $K_v, I_v$ - the capital investment and the cost of step $v$;
- $\tau$ - the number of year to complete construction;
- $T$ - the period of system’s development;
- $\theta$ – step of digitization;
- $E$ - coefficient of comparative effectiveness of investments - reciprocal of the payback period, which is recommended to be defined by projected tariffs for communal services [5.6];
- $(1 + E)^{\tau - \theta (v-1)}$ - coefficient that takes into account the reduction in the importance of cost, carried out by $t$ years;
- $I_n$ - the costs of normal operation after completion of construction of the sewerage system.

For example, the sewerage scheme is designed for 15 years ($T = 15$), will be implemented in three stages ($V = 3$) in three investment programs by five years per time ($\theta = 5$), year of bringing cost - the number of year to complete construction ($\tau = 15$), payback period of 6 years ($E = 0.16$). Moreover, if the existing sewerage system is being reconstructed and developed, in construction of the first stage, investment will carry out the reconstruction of existing and construction of new pipelines and facilities, and the costs at this stage (for 5 years) will be associated only with the operation of the existing sewerage system. In the construction of the second stage, costs would apply to the operational costs of the existing network and new one, that has been built in the first stage and put in operation, etc. to the implementation of the third construction stage, when full (normal) operating costs arise, which are reflected in the formula (1) in the form of last term. Therefore, as a criterion of optimization for each stage, of making a decision will have the following costs:

$$Z_v = K_v^n \cdot \left(1 + E \right)^{\tau - \theta (v-1)} + \theta \cdot I_v^n \cdot \left[ \left(1 + E \right)^\theta - 1 \right]$$

(2)

where $K_v^n, I_v^n, I_n^n$ - investment in new and reconstructed buildings, costs of new and existing buildings.

It appropriate to take the cost for design, construction, reconstruction and operation of pressure and gravity pipelines and pumping stations as a major capital investment and expenses. The cost of other buildings is taken into account in the enlarged index. To concretize one-time and operating costs, we propose to use the information, which is contained in the construction price norms: NCS 81-02-14-2012. "Water Supply and Sewerage networks", in the document: "The estimated norms and pricing of new construction technologies."

It is sensible to assess sewerage system reliability, seismic resistance and environmental safety by quantitative measure - the volume of untreated effluent that is formed over a certain period of accidents and its elimination. In the study [7], volume of wastewater is proposed to calculate by the intensity of breakdown and restoration of existing and planned pipelines. Where in seismic resistance is considered by increase of the breakdown’s intensity in depending on the earthquake intensity and its orientation [8]. The technique of optimization of sewerage systems with considering of the reliability and seismic resistance is clearly described in study [9].

Obviously, the costs must be added with the cost of prevention of untreated sewage input to the surface or the cost of their transportation and treatment at wastewater treatment plants.

With considering the above reasoning, we can formulate the problem of optimal development management of sewerage systems as follows. We have to find a network structure and sewerage system flows, that would provide a minimum cost in its phased construction, operation, and prevention of accidental untreated sewage input to the surface and water body.
To assess every possible option of development and the stages of its implementation, we propose a complex of models and methods of analysis, parameters’ optimization, and operation modes of new and reconstructed sewerage systems [10-13]. The selection of a preferred option is taken under limited investments, which are defined by the investment programs at every stage of the development of sewerage systems.

Variation of sewerage systems development occurs during the construction of first phase, system’s parameters can be designed by the pass of first stage, all stage, and their combinations’ effluent, and the same applies to the second, third, etc. constructive stages. It is not difficult to see that the number of options for sewerage system development depends on quantity of construction stages and it is calculated by the following formula $K = V!$, where $V$ - the number of construction stages, $!$ - factorial. For example, for the construction of three stages, development’s options will be 6, four - 24, five – 120, for fifteen - 1307674368000. It should also be noted that the number of options for the development of sewerage system depends only on the number of planned construction stages and does not depend on the chosen development scheme of the city and its engineering systems.

Obviously, simple choice of development options is possible for no more than five stages of sewerage systems construction may be. In other cases, it requires developing optimal approaches and methods. One such method is proposed in this study. This method is based on a multi-step process to optimize the parameters of reconstructed and new sections of the network and facilities with the preliminary construction of the graph of possible transitions sewerage system from one condition to another.

Such graphs for the construction of sewerage system with three, four and five stages are shown in figure 1. In this figure, $Q_1$, $Q_2$, $Q_3$... - load of the first, second and third stage in construction.

**Figure 1.** Graphs of possible transitions of sewerage system, implemented in three (a), four (b) and five (c) construction stages.

In essence, the proposed approach in this paper is a complex multi-level computational process, in its top level, a scheme of dynamic programming is implemented to build the multiple of conditionally
optimal trajectories of system development. On the next level, the problem of sewerage systems synthesis is solved which provides the best evaluation of "stackable" development trajectories with the checking of their technical and financial feasibility. After building of all the possible development trajectories, we choose the best of them and this trajectory and parameters of sewerage system in the construction stage are restored back. This functional equation of optimal development management of sewerage systems will be as follows:

$$Z_i(\sum_{j=1}^{V} Q_j) = \min \left\{ Z_{i-1}(\sum_{j=1}^{V} Q_j) + \Psi(\sum_{j=1}^{V} Q_j) \right\}$$ (3)

The function $\Psi(\sum_{j=1}^{V} Q_j)$ - would be consistent with the optimal criterion costs (2) in the construction of new and reconstruction of existing network sections, including operating costs. If the value of investments in the construction of the sewerage system at some stage of its development is known, the transition option from $\Psi(\sum_{j=1}^{V} Q_j)$ exceeds this value, it is excluded from further consideration.

It is worth noting that many parameters, which are designed on the prospect of sewerage systems are not defined or have a probabilistic character. At a closer time interval, the flow of information can be considered as deterministic, at subsequent - as the conditional probabilistic and uncertain (in the sense of interval uncertainty). Over time, there is a "withdrawal" of information uncertainty, that is, the information transfers from the uncertainty to conditional probability and from conditional probability to deterministic. Obviously, in the selecting of optimal structure and parameters of sewerage systems in the early stages must take into account the next possible states.

If some basic information is given in the probabilistic form, the condition of transition (3) from the state $V-1$ to $V$ can be considered as the mathematical expectation of costs in their development and reconstruction:

$$\Psi^* = \sum_{j=1}^{V} \rho_j \cdot \Psi(\sum_{j=1}^{V} Q_j)$$ (4)

where $\Psi^*_{v,g}$ - the mathematical expectation of the system’s development; $\rho_j$ - the probability of analyzed values of information; $N$ - the number of these values.

From the computational point of view, this leads to an increase of transition graph’s dimension and of the sewerage system’s analyzed trajectories at each time phase to $N$ times.

In the case of interval uncertainty of the initial information, value $\Psi^*_{v,g}$ can be calculated either by expert estimations or through the Wald, Savage, Bayes, Hurwitz, Laplace criterion etc. [14, 15].

3. The numerical experiment

Take the example of a consistent development of sewerage system in four stages (figure. 2), the graph of possible transitions for which is shown in figure.1b. On figure.1d red lines show the optimal development trajectory of sewerage system, that are received by the proposed methodology. Figure. 3 shows the results of calculation, according to which, the section 8-7 at different stages of construction requires install three parallel sewers, sections 9-8 requires two parallel sewers, sections 1-7, 10-9, 11-10 require one parallel sewers.
4. Results and discussion
If allocated investments for the implementation of the first stages are known in advance, the substantiation’s technique of its parameters is simplified and implemented in one phase. In so doing, the calculation is carried out on load pass of wastewater from all residential areas, and in the optimization model, restrictions are imposed "required investments should not exceed the allocated" [18]. The proposed method is implemented in the software system TRACE-VR which is successfully used in justifying prospective schemes of sewerage system [19, 20]. When specifying hydraulic relations and technical-economic indicators of the proposed method can be applied in justifying promising schemes of electric power and pipeline systems of housing and communal services.

5. Conclusions
There is a new formation’s method of development options, analysis and parameter optimization of the developing sewerage systems with limited investment in their construction. It corresponds to market relation, which enters deeper into this vital industry - housing and communal services. This methodology makes it possible to take account deterministic, probabilistic character and interval uncertainty of information about the state of sewerage system in the future and embodies the principle "make a decision with a minimum earliness".

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