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Using GIS Concept for Management and Enhancement of the Sewage System in Cities with Sudden Population Change

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The process of urbanization with a sharp change in the population in cities creates conditions of hydraulic overloading of both water supply and wastewater disposal systems and treatment plants. The need to expand, improve, improve the quality of management and reliability of operation of sewage systems requires the use of modern technology, namely GIS geographic information system. The purpose of this paper is to investigate the capabilities of geographic information system in the improvement and management of sewerage system in cities with dramatic changes in population.Results and Conclusion This paper describes the peculiarities of sewerage systems and justifies the necessity of preliminary engineering-geological surveys in the construction of urban wastewater disposal systems. Interactive maps created on the basis of GIS display geodata and attribute data obtained from scanned documents, aerial and space images, and photographs. Data organization in GIS allows to change visibility and order of layers during map visualization, to carry out independent adjustment of parameters of each layer, to make independent spatial analysis by layers, and also to form maps from layers of different degree of detail and origin. The stages and methodology of modeling the sewerage system in the construction of new city districts or for monitoring and management of sewerage networks using the ArcGIS software package are given. Thus, the paper shows the capabilities of GIS for problem identification, change tracking, event management and response, and forecasting. GIS technologies allow to reduce labor costs and, consequently, economic costs of the budget, and significantly improve the quality of network management.

Keywords: Sewage system, GIS, Interactive maps, Wastewater systems, electronic map layers.

1. Introduction

An important indicator in the design of the urban wastewater disposal system is the forecasting of the city development, its demographic and urban planning prospects. For example, industrial development provides for the development of the territory with residential buildings (complexes), kindergartens, schools, physical culture and sports facilities and socio-cultural facilities. Estimated wastewater flow rates are determined based on the degree of improvement of residential development and retained housing stock. At the same time, specific norms of wastewater disposal are assumed to be equal to the norms of water consumption (Chupin et al., 2023)(Singh & Singh, 2017). Reserve capacity of sewage pumping stations and sewage treatment facilities should be, but without taking into account the expansion of the wastewater disposal system by connecting new facilities. The existing reserve is necessary when strengthening the system to cover the uneven loading of the elements of the drainage system (Hund et al., 2021)(Minh et al., 2017). It is inexpedient to build up a large reserve of equipment capacity due to a significant increase in energy consumption. In case of a sharp increase in the city's population, it is necessary to expand the sewerage system, as the reserve does not cover the needs of new connections. First of all, it is necessary to abandon the general sewerage system and divide it into domestic and storm sewerage (depending on climatic conditions). Next, reconstruction or expansion (construction) of the drainage network in general, sewage pumping station and sewage treatment facilities, in particular, is required (Recycling., 2024)(Ambulkar & Nathanson, 2023).

The main directions of reconstruction and re-equipment of objects of the system

Wastewater disposal system facilities are (Tolipov et al., 2023)(Serdarevic & Dzubur, 2019):

- Increase in the volume of wastewater services,

- Reliability (continuity) of wastewater services,

- reducing the cost of wastewater services,

- Achievement of quality standards for wastewater treatment at treatment facilities.

Reliable and efficient operation of the wastewater disposal system of cities is one of the most important components of their sanitary and environmental well-being. And here the priority is to improve the quality of water treatment, reliability of networks and facilities, reducing the risk of emergencies (Janke et al., 2013).

Normal functioning of wastewater disposal networks is associated with limiting the degree of filling of gravity lines. In addition, the probability of backflow is reduced, which causes water infiltration and contamination of the ground and groundwater, sometimes it can lead to the overflow of wastewater to the surface. In the case of pressure pipelines, anaerobic conditions favorable to the formation of highly toxic hydrogen sulfide are created in them. And failures of sewage pumping station led to emergency water discharge into drains or water bodies, i.e. to unacceptable violation of environmental requirements (Ehalt Macedo et al., 2021)(Kesari et al., 2021).

When considering the possibility of using the reserve of collectors, pumping stations and treatment facilities, it is necessary to take into account the wear and tear of pipe material, equipment, the lack of modern energy-saving equipment, automation, non-compliance of existing technologies of sewage treatment and sludge treatment with modern requirements of environmental protection authorities(Sewerage Systems," Britannica, n.d.).

During engineering surveys for design and construction of linear structures, especially sewerage facilities, it is necessary to take into account a number of specific complexities. The creation of sewerage facilities requires a special approach, because in these cases, first of all, it is necessary to solve the issues of excavation works. Therefore, it is necessary to take into account geomorphological, geological, hydrogeological and anthropogenic factors that affect the implementation of underground sewerage network projects in many ways (Niemiec et al., 2020)(Mailyan et al., 2021).

2. Peculiarities of Design, Construction and Improvement of the Sewerage System in Cities

Domestic, rain and industrial wastewater is discharged into the municipal sewerage system. The sewerage system is a rather extensive and expensive complex of special facilities designed for the operational removal of wastewater from settlements and its treatment before release into the receiver.

The sewerage system of a city or industrial enterprise consists of the following main elements (Portnov et al., 2021):

- Internal house or in-house sewerage devices, designed to receive wastewater and take it outside the premises. In this case, in residential and public buildings sewage receivers are sanitary devices, and at industrial enterprises - special receivers in the form of funnels, traps, trays, which are installed directly at the apparatus and machines;

- External sewerage network (yard, factory, intra-block, street, etc.), consisting of sewerage pipelines, as well as collectors (collecting sewage from street lines, including rainwater) and the main collector. If the terrain is favorable, wastewater is discharged by gravity. Otherwise, pumping stations are installed in depressed areas of the sewered area, which pump wastewater to treatment facilities or to a higher-lying collector, from where it is transported by gravity to the place of treatment;

- Treatment plants designed for full or partial treatment of wastewater before discharge into a water body or use in irrigation fields.

The carrier sewer pipe, as the entire city pipeline is consolidated into a single discharge main, is characterized by a diameter that gradually increases toward the sewer. This pipe has a very large diameter, and laying such a pipe is a rather laborious and expensive process. Since it is not always possible due to the terrain to organize the drainage system by gravity, special pumps are required. Further getting to the treatment facilities wastewater is purified in basins (tanks) with the help of chemicals and special additives. A necessary condition in the modern construction of drainage systems is the separation of domestic and storm water, which is associated with different methods of their treatment (V., 2024).

Practice shows that pipe networks are not only the most functionally significant element of the drainage system, but also the most vulnerable in terms of reliability. In order to reduce the time of wastewater leak detection, it is advisable to automate this control with the help of modern computer technologies (Ehalt Macedo et al., 2021)(A. R., 2024). The main economic indicator for pipelines in the wastewater disposal system of large cities, especially for non-pressure pipelines, is the cost of their construction, which is influenced by a large number of factors (Welling & Sinha, 2013).

In modern conditions, the management of a territorially distributed system of urban engineering networks is impossible without information about the spatial structure. To improve the efficiency of water supply and sewerage systems, innovative and locally adapted technologies should be used.

When designing sewerage facilities, it is advisable to conduct geophysical studies of the section along the line of the structure, to investigate soil samples. However, such works are not always carried out (McClymont et al., 2016).

Construction of sewerage facilities without preliminary engineering-geological surveys generates a number of difficulties that increase construction time, financial costs, and in some cases lead to destruction. Also, a similar disadvantage associated with the lack of engineering-geological surveys is that the excavation of soil is not taken into account its type and moisture, which can lead to a significant increase in the cost of the entire project. The closer the groundwater is to the surface, the more complicated the process of project realization or network reconstruction. Another feature of such surveys is the availability of sufficient material for backfilling the pipes. The most important characteristic in terms of construction or reconstruction of wastewater disposal systems is the cost of excavation (Niemiec et al., 2020)(Rushton, 2004)(Civillearners, n.d.).

During geotechnical engineering surveys, it is important to focus on the following in more detail. Firstly, it is necessary to pay special attention to the areas where the rocks come to the surface. On them, the creation of trenches will be more expensive and technically complex (e.g., using blasting, impact machines). Another important aspect is to find out if there is rock bedrock within the planned trench depth along the entire trench route. The closer it is to the surface, the more expensive it is to create the trench. It is not only necessary to take into account the possible increase in construction costs, but also to choose or adapt the excavation methodology correctly.

3. GIS Capabilities for Wastewater Systems

Currently, for data processing in the design, construction and management of linear objects, GIS geographic information systems are increasingly used, which provide collection, storage, analysis, and graphical visualization of spatial data and information about objects. The main principle in the visualization of spatial data in GIS is their layer-by-layer organization (Fig. 1) (Khorolsky et al., 2020). The same type of data similar in semantics, dimensionality or topological structure is grouped into layers.

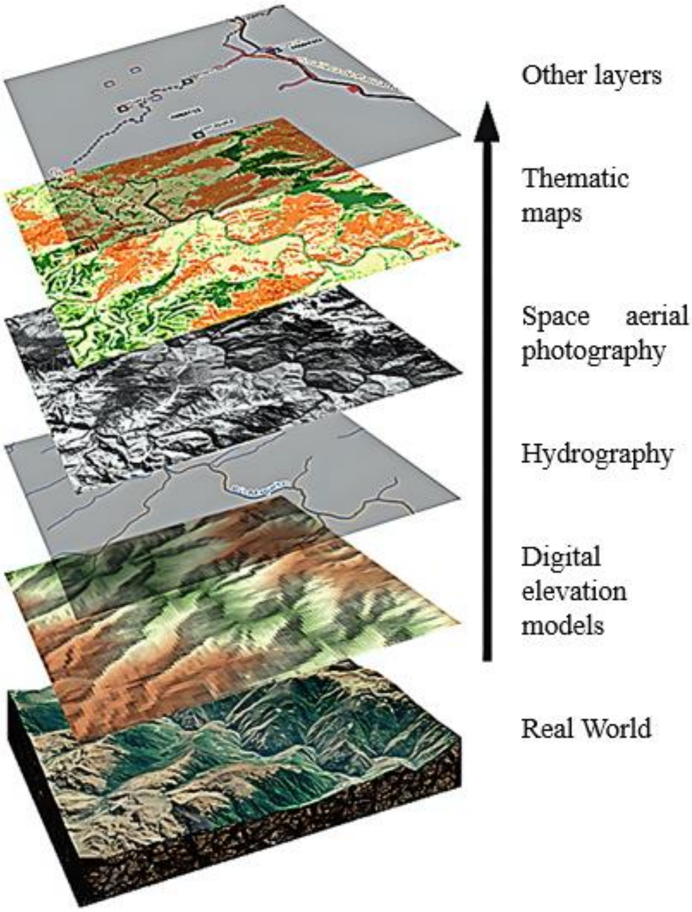

Figure 1. Layers of the electronic map.

This organization of data in GIS allows (Spatialpost, 2017)(Tableau, 2024):

- change the visibility and order of layers in map visualization;

- To carry out independent adjustment of visualization parameters of each layer;

- perform independent spatial analysis by layers;

- form maps from layers of different levels of detail and origin (Fig. 2).

Due to the wide geographical coverage, it is also advisable to manage and improve urban sewerage networks using GIS. Interactive maps created on the basis of GIS display geodata and attribute data obtained from scanned documents, aerial and space images, and photographs. GIS technologies allow to reduce labor costs and, consequently, economic costs of the budget for the design of various urban engineering systems, including sewerage. Urban wastewater assessment is very important in the risk- and cost-effective design of the sewerage network. For example, managing a capital improvement plan for drainage networks that can cost thousands to billions of dollars has inherent challenges that can affect the schedule, quality, cost, and reliability of the infrastructure (Chamoux & Gourbesville, 2003)(R. R., 2024).

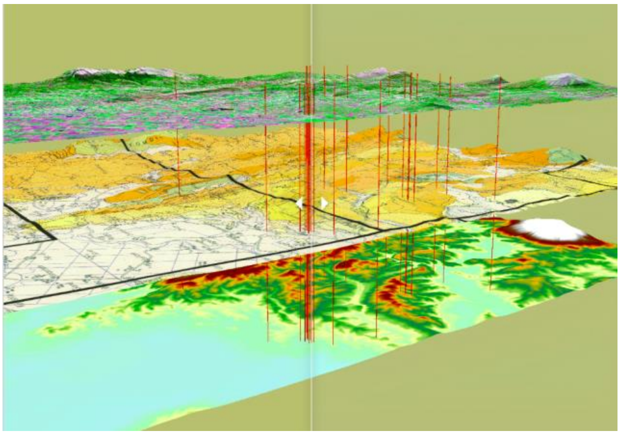

Figure 2. Forming a map by overlaying layers.

Due to the wide geographical coverage, it is also advisable to manage and improve urban sewerage networks using GIS. Interactive maps created on the basis of GIS display geodata and attribute data obtained from scanned documents, aerial and space images, and photographs. GIS technologies allow to reduce labor costs and, consequently, economic costs of the budget for the design of various urban engineering systems, including sewerage. Urban wastewater assessment is very important in the risk- and cost-effective design of the sewerage network. For example, managing a capital improvement plan for drainage networks that can cost thousands to billions of dollars has inherent challenges that can affect the schedule, quality, cost, and reliability of the infrastructure (Sweetapple et al., 2018)(Stroymaps, 2021).

Hydrologic parameters of watersheds can be determined using tools in GIS environments and digital elevation and land use models from aerial photographs. The data can be used to model hydrological processes in urban catchments and the hydraulics of sewer networks (Chamoux & Gourbesville, 2003).

Due to the graphical visualization of heterogeneous information such as terrain, soil quality, etc., which should be taken into account when designing such systems, GIS allows to quickly consider several options of solutions with the selection of the most effective one.

All elements of a sewer system can be categorized into spatial features: points, lines and areas. Pressure pipelines, open and closed channels, etc. are represented by lines, which have their own set of more or less independent characteristics. Revision shafts, drains, pumping stations, culverts, related to nodal objects and catchment areas through which sediments enter the system, are areal objects. The relationship between the objects is represented at graphical and topological levels [39-32]. All the objects of the system are related to its graphical representation, and the connection to the topological level is achieved and stored as an attribute of each object. A GIS model of sewerage systems should have the following properties:

- Graphical and geometric representation of data in 3D with the possibility of adding and modifying object properties,

- object connectivity at the topological level, management and control during operation.

Continuous maintenance is an extremely important component to help avoid and correct errors. The database and its ability to control and manage data plays a major role in this segment. Some of such GIS based software products for sewerage are Bentley WasteWater, ProGIS, ArcGIS.

The development of geographic information systems and hydraulic models allows identifying “weak” places in the wastewater system, monitoring and managing the systems. Specialized industry product ArcGIS Solutions allows solving a large number of tasks [33]:

- Capital improvement planning;

- monitoring public information on sewer clogging, flooding;

- sewer data management allows you to display sewer facilities, edit data, view system maps, and work with map notes;

- indexing the geographic coverage of plan and drawing records and providing access to a catalog of source documents.

For example, the ArcGIS software package can be used to model a wastewater system for the construction of new city districts or for monitoring and managing sewer networks.

At the first stage, a specific area with wells, pipes and outlets directly within the boundaries of the site is allocated. This area is then broken down into polygons. Based on the previously loaded pipes and wells, calculated sections and points are modeled. Modeled polygons (sections, points) are filled with attributes - section lengths, pipe diameters, bottom marks of section points, etc. For each polygon the point where the runoff arrives is specified. The area of each polygon is calculated.

At the second stage, pipes and polygons are loaded into a software package, for example, the civil 3D computer-aided design system. The plot of water flow in each polygon is built and by them the program determines the time of water leaving to the wells.

Then for each polygon the scheme is imported into Autodesk Storm and Sanitary Analysis, a modeling software package for analysis and design of urban drainage systems, storm drains and sewers (Fig. 3). Complex hydrology and hydraulics can be modeled here.

After setting up the scheme, a hydraulic calculation is carried out on the basis of data on pipe diameter and length, catchment area, etc. According to the profile of the design pipes, at the end of the hydraulic calculation (pipes are highlighted in red color), it is possible to draw a conclusion about the operating mode of the pipes, which determines the possibility of further operation of the pipe or its replacement. Also, on the scheme critical areas subject to waterlogging during heavy precipitation are highlighted in red color. Thus, the analysis and identification of potential emergency areas of the sewerage system is carried out, which allows preventing an emergency situation and increasing the level of reliability of the entire sewerage system.

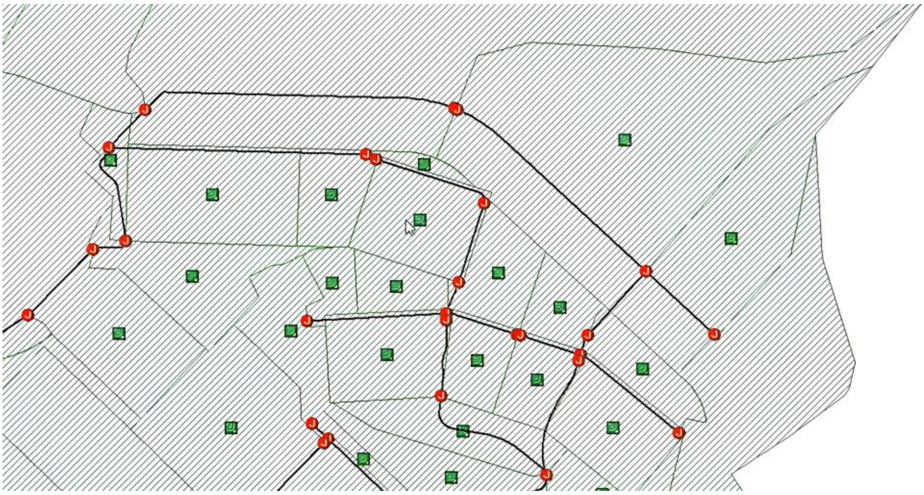

Figure 3. Calculation scheme.

4. Conclusion

Reliable and efficient operation of the wastewater disposal system of cities is one of the most important components of their sanitary and environmental well-being. The priority in the operation of the sewage system is to improve the quality of water treatment, reliability of networks and facilities, and reduce the risk of emergencies. GIS provides solutions for wastewater systems, enabling utilities to monitor changes in the system, identify problems, respond to them, perform advanced analytics, visualization and information exchange between systems to easily collect and manage infrastructure data, which increases the efficiency and reliability of the network.

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