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## 1.7 Modeling of runoff hydrographs from the impervious subcatchments by using CFD

The problem of urban areas flooding, due to increasing the volume of surface runoff, in Ukraine is exacerbated by growing urbanization trends, climate change and the problematic technical condition of sewerage networks. The analysis indicates that the urgency of this problem will increase in the coming decades. This encourages the scientific and engineering community to develop runoff management strategies and plans, as well as to widely introduce surface runoff control systems into Ukrainian engineering practice, which must be scientifically proved and adapted to local climatic, urban, and economic conditions.

The problem of flooding urbanized areas in Ukraine due to the increase in volumes and costs of surface runoff is exacerbated by growing urbanization trends, climate changes, and the problematic technical condition of drainage networks. The analysis indicates that the urgency of this problem will grow over the following decades. This prompts the scientific and engineering community to develop stormwater management strategies and plans and to widely implement surface runoff regulation systems into Ukrainian engineering practice, which should be scientifically based and adapted to local climatic, urban planning, and economic conditions.

The reliability and durability of rainwater drainage systems, and the ability to effectively process their peak loads for cities and small towns, as well as industrial enterprises, is an important component of ensuring the normal functioning of the sewage system as a whole and significantly affects the ecological state of the environment. Peak loads on the drainage network during heavy rains pose a threat to the normal functioning of both the network itself and treatment facilities: the danger of overflowing the network and flooding the facility territory increases, the probability of a deterioration in the quality of surface runoff treatment or its mixture with household and household runoff increases sharply industrial wastewater. For the adequate design of rainwater drainage networks and structures, scientifically based modeling of rainwater inflow hydrographs is of great importance, in which geographic, topographic, and other features of the object should be considered as fully as possible.

To date, there is no single, universally recognized method for modeling rainwater runoff hydrographs from urban basins in the world. Most of the known mathematical models of rainfall-runoff modeling use significant simplifications due to the limited use of the capabilities of modern information systems or are based on the data of specific empirical studies that have a narrow range of applications. Thus, the improvement and addition of physically based models for the construction of rainwater wastewater hydrographs, which would describe the topographical, climatic, and physical features of the drainage basin as correctly as possible, is especially relevant, considering the modern trends of urbanization and climatic changes.

Modeling the behavior of surface runoff from urbanized areas is a complex multifactorial problem facing specialists and scientists worldwide. With each subsequent decade, the number of urbanized areas increases, which affects the volumes of rainwater runoff, and increases the load on city sewage networks, sewage treatment plants, and accordingly, open water bodies. To ensure the reliable operation of sewage networks, it is necessary to consider different modes of their operation (including peak loads), as well as factors such as changing climatic conditions and the rapid growth of areas of urbanized neighborhoods. To solve these problems, several approaches were developed to study the processes of surface runoff formation. In general, there are dozens of models for calculating rainfall runoff hydrographs that have been developed by scientific institutions, government departments, and international organizations. During the development of these models, various approaches were used, and many parameters were considered to ensure the reliability of the obtained results.

The works of Akan O. [67], Guo D. [69], Ibrahim Y.A. [73] are devoted to the problems of hydrological and hydraulic modeling of rain runoff in natural channels and engineering networks and structures Bennis S. and others [68]. General issues of regulation of rainwater runoff from urban areas were considered by Zoppou C. [76], Dziopak Y., Huber V., Shuler T. and others [72]. Methods of hydraulic calculation and modes of operation of storage facilities for regulating rain runoff are analyzed in the works of D. Guo [70], Y. Dziopak [71], V. M. Zhuk [75], and others.

The analysis of scientific works and modern engineering and technical practices shows that today there is no single generally accepted approach to the formation of rain runoff and the correct modeling of this process. The existing models are based on significant simplifications, often do not consider the hydraulic essence of the processes that take place during the formation of rain runoff, are purely empirical in nature, and have a limited range of applications. Attempts to consider additional factors significantly complicate mathematical models and require significant computing resources, which cannot always be implemented in practice. The block of issues related to the development of methods and technologies for efficient and economical regulation of rainwater runoff from urban sewage basins is insufficiently worked out.

Thus, the development and application of new, improved methods of modeling rainwater runoff hydrographs from urbanized areas, which would consider the topographical, climatic, and physical features of runoff basins as fully as possible, as well as allow for effectively regulate the operation of rainwater drainage systems, are urgent tasks in the field of construction and civil engineering.

Among the modern methods of modeling rain runoff, deterministic and stochastic ones can be distinguished. Deterministic models seek to perfectly simulate physical processes using cause-and-effect relationships. Stochastic models use statistical patterns of a specific phenomenon to model this phenomenon. However, in practice, there is no clear and absolute difference between deterministic and stochastic models. Deterministic models have varying degrees of uncertainty or randomness built into their general formulations and parameters, while stochastic models do not completely ignore cause-and-effect relationships. To distinguish between the two modeling approaches, it has been proposed that a deterministic model always produces the same response to the same input, while a stochastic model always produces a different response to the same input, albeit with consistent statistical properties. Both deterministic and stochastic models often use empirical models as part of their mathematical algorithm to describe the relationships between variables that are considered relevant to modeling the process. Thus, empirical models do not strictly represent a separate class of modeling alongside deterministic and stochastic models but are rather a subcategory of both deterministic and stochastic models. Each of the deterministic and stochastic models has serious limitations. Deterministic models do not consider the uncertainty of variables. Complex deterministic models may contain multiple optimal sets of parameters, in which case no set of parameters can be identified as a set of unique solutions. The heterogeneity of parameters was observed in both models. Stochastic models are synthesized only from available data without detailed knowledge of the hidden processes and may be insufficient for prediction when data are sparse or imprecise.

Unlike deterministic models, stochastic models cannot be extended to analyze alternative scenarios (for example, the impact of increased urbanization on the increasing number of pollutants contained in stormwater), because a stochastic model can only be used for specific conditions and data on which based model. However, stochastic models are advantageous in that the uncertainty of the variable is built into the model.

In his works, Nix [74] singles out three main strategies used to model rain runoff:

• simple models.

• simple models with routing (models that use basic routing models).

• complex models with a developed rainwater routing model (models in which a complex mathematical routing logic is embedded).

Each category has different requirements for data and computing resources and provides results at different time scales and spatial dimensions. In simple models (models where routing is not used), little data is required, and the calculations are not repeated cyclically, so these calculations can be performed without the use of computers. These models provide very little detail about the flow behavior of stormwater runoff. In general, these models are used to calculate long-term, average, or peak values of characteristic parameters. They are specialized for a specific case. Empirical models can be considered simple models. Although some statistical models are based on complex techniques, they reflect only the current behavior of the subbasin runoff in a certain area. Some empirical models predict very simple dependencies that do not require the use of computer simulations. Both simple and complex models are based on physical laws that describe the flow of rainwater on the surface of the drainage basin. Although these are deterministic models in their physical essence, they describe the behavior of subbasin runoff under various possible configurations. The complexity of the model affects the volume of necessary computing resources and limits the calculation capabilities of the model and the reliability of the results obtained from it.

The results of simple models can also be obtained using more complex models, but the reverse process cannot be implemented. Simple stormwater flow models do not simulate some important processes. For example, a linear tank routing technique common in the past is a simple generalized model. Time-dependent processes cannot be modeled because all processes are assumed to occur instantaneously. To overcome this problem, models include time, such as flow delay in the routing process. This introduces another subjective factor that can be specified by the user, and this approach is independent of the behavior of the simulated process. Combined models are typically used in planning models where the time steps significantly exceed the interval of transients that occur in the system, so they use average values for different processes. At the same time, the temporal and spatial variability of the system, which is necessary to check the integrity of the rainwater system, is ignored. They must be artificially added to the modeling process. Therefore, it is necessary to establish an empirical relationship between peak and average flows in the rainwater drainage system. This creates additional subjectivity and uncertainty in the modeling process. These problems can be overcome by using more complex models, at the same time, the latter is more costly in terms of resource use and requires complex calculations using computer equipment.

All previously performed studies were focused on experimental aspect and well organized and performed studies of this phenomena. Thus, despite computational fluid dynamics (CFD) becoming an extremely important method which can be used for investigations of the hydraulic problems.

Numerical simulations were performed using the COMSOL Multiphysics simulation software. Its two-phase solver, which is based on the volume of fluid (VOF) method, has been proven to successfully model complex flows.

To perform comparisons of the experimental results and results obtained with CFD modeling was created a numerical model in the Multiphysics simulation software platform (figure 1.).

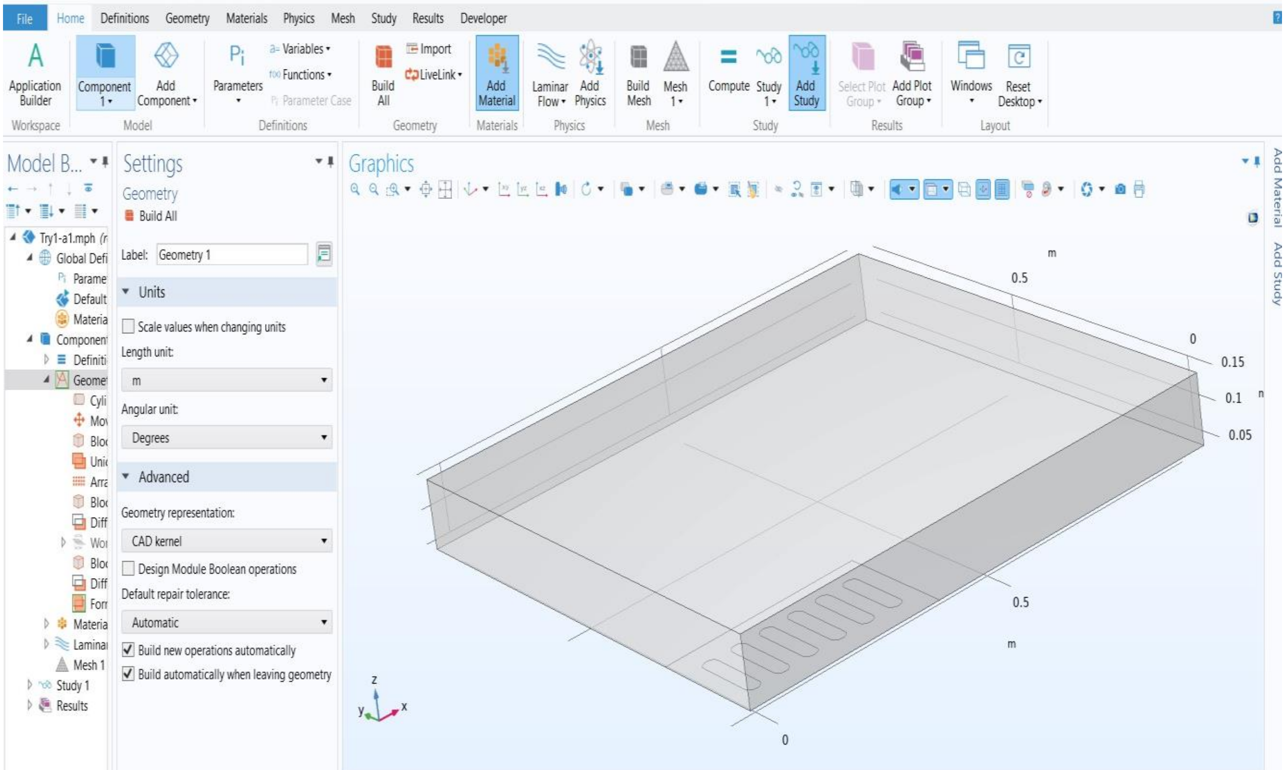


Fig. 1. Model setup with COMSOL Multiphysics simulation software.

The boundary conditions applied to the numerical model was following (figure 2.): inlet ($u = u_0; \nabla p = 0.$); outlet ($\nabla u = 0; \nabla p = 0.$); wall ($u = 0; \nabla p = 0.$); atmosphere ($\nabla u = 0$; $p = 0.$).

In order to match the experimental conditions, the inlet boundary was applied to $U$ ($u=u_0;$) which adjusted the flow depth and velocity at the inlet to obtain a constant flow rate ($Q$). The outlet boundary was equalized to a zero gradient velocity condition in the model, which was achieved by Neuman BC condition ( $\nabla u = 0$; $\nabla p = 0$). The no-slip boundary condition was applied to the surface of the subcatchement by choosing wall condition ($u=0$; $\nabla p = 0$). The top surface of the model was considered as a free surface (atmosphere), so, for *U* was imposed to allow the flow to enter and leave the simulation domain.

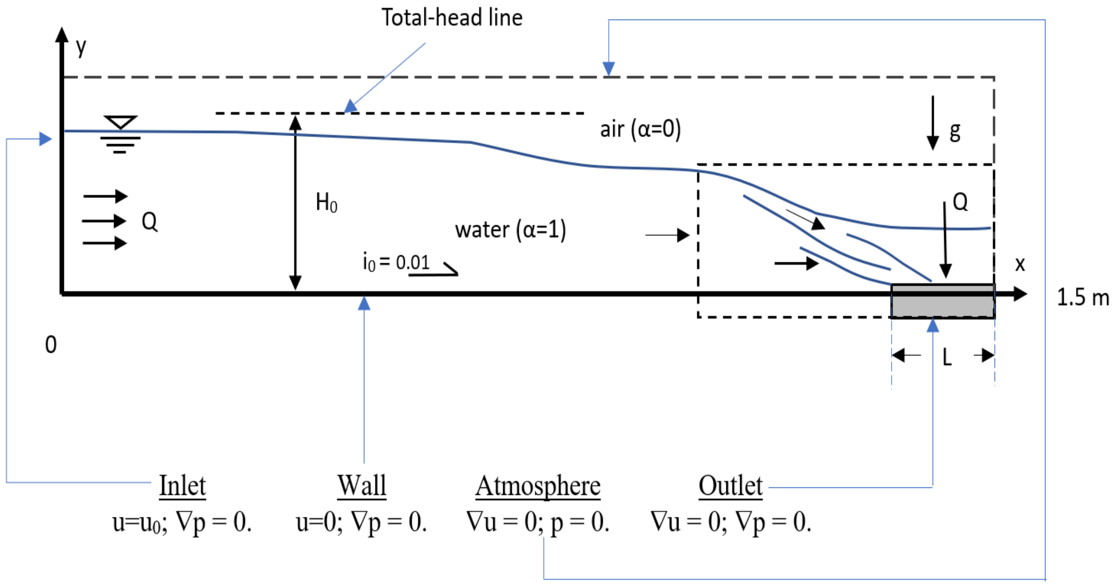


Fig. 2. Boundary conditions using COMSOL Multiphysics simulation software.

The mesh of the model (figure 3, 4) was generated automatically by the COMSOL Multiphysics simulation software. The Mesh features enable the discretization of the geometry model into small units of simple shapes, referred to as mesh elements. For 3D geometries, the mesh generator discretizes the domains (intervals) into smaller intervals (or mesh elements).

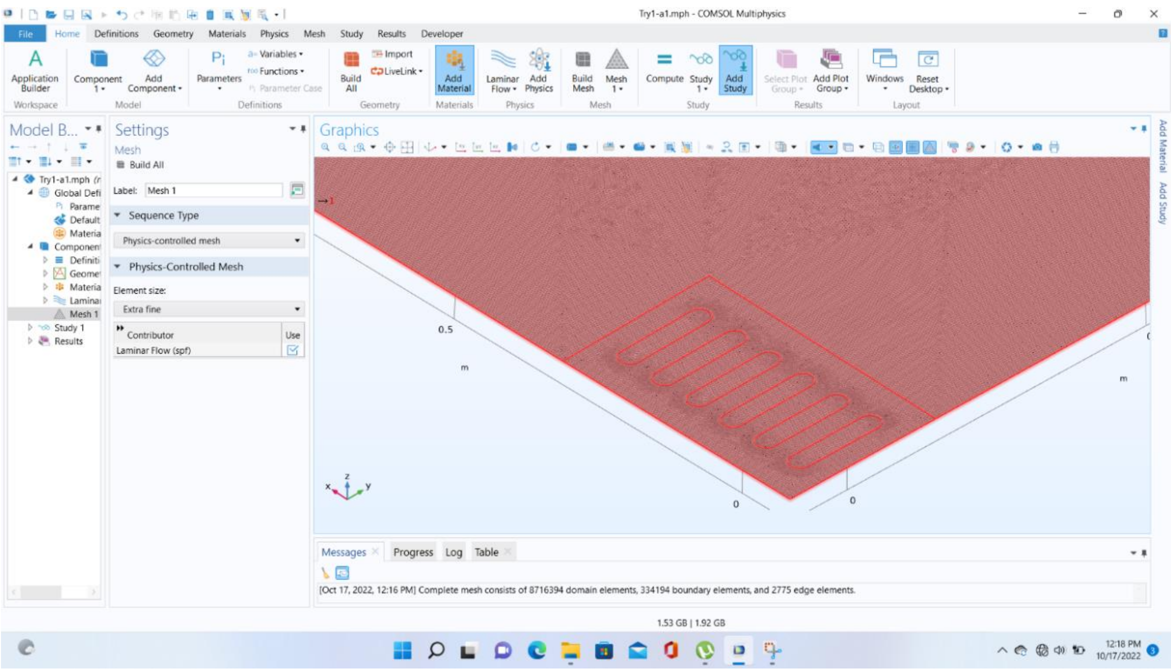


Fig. 3. Mesh generated near grate inlet model.

The endpoints of the mesh elements are called mesh vertices. The boundaries (or vertices) defined in the geometry are represented in the mesh by boundary elements (or vertex elements).

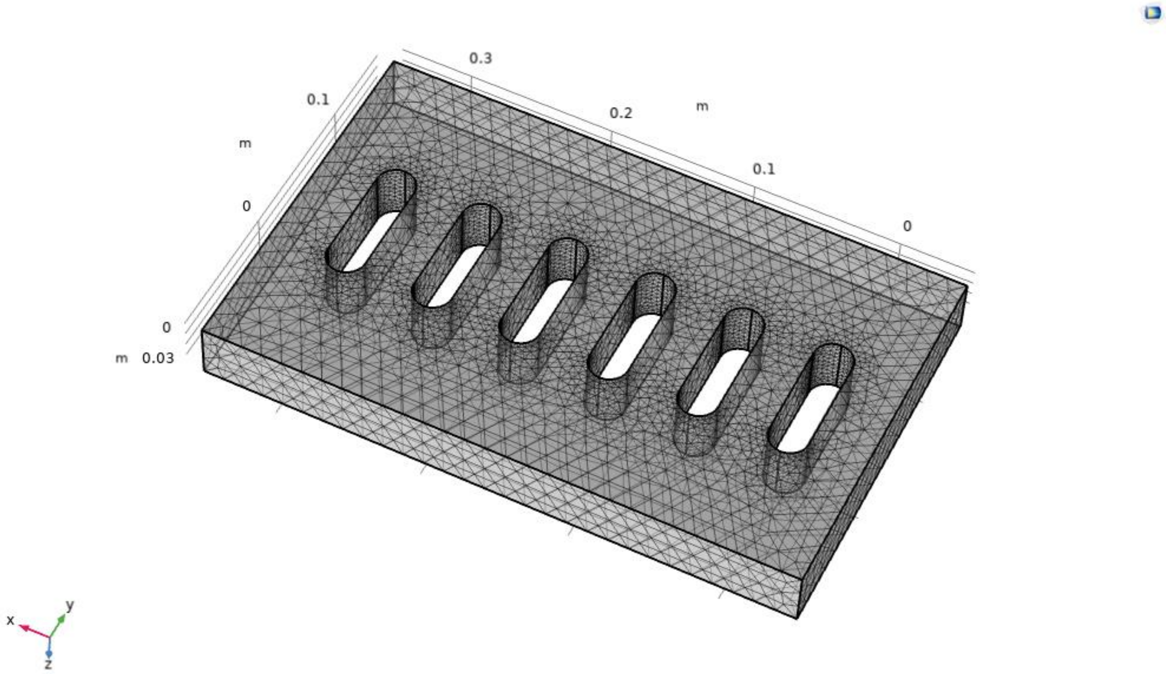


Fig. 4. Mesh generated for great inlet type DM-1 model.

For 3D geometries, the mesh generator discretizes the domains into tetrahedral, hexahedral, prism, or pyramid mesh elements whose faces, edges, and corners are called mesh faces, mesh edges, and mesh vertices, respectively. The boundaries in the geometry are discretized into triangular or quadrilateral boundary elements. The geometry edges are discretized into edge elements.

In current research was used physic-controlled meshing. It is the default approach when mesh is controlled by the physics module applied to the model. The mesh is then adapted to the current physics settings in the model.

In this work, an important scientific and practical task was solved, namely - development of new and improvement of existing methods of runoff modeling in the built-up territories with reflecting regulatory influence of separate elements of drainage constructions.

The results of the work are important for ensuring the comprehensive reliability of settlement’s drainage systems in Ukraine in the conditions of constant growing tendencies of urbanization processes and considering global climate changes. The determining factor for the development and implementation of adequate practical plans for surface runoff management is its scientifically substantiated modeling, which is carried out according to the climate characteristics and parameters of the runoff basin, considering the ranges of their projected change over time.

Modeling the behavior of surface runoff from urban areas is a complex multifactorial problem. It is substantiated that reliable results of complex stormwater drainage networks modeling with the addition of control structure's role can be obtained only with the use of multifactor numerical models implemented in the appropriate computer programs.

The analysis shows that the most widely used tool in the world today for computer simulation of stormwater drainage systems in urban areas is the software package COMSOL. However, COMSOL uses several simplified approaches to model the hydrological and hydraulic parameters of stormwater drainage systems. To model the primary runoff hydrographs from individual runoff subcatchment, an approximate nonlinear reservoir method is used, in which a subcatchment of arbitrary shape is conventionally considered as a rectangle with equal area (which have a length equal to the surface flow concentration radius), and the slope of the basin is assumed to be the same at all points.

Numerical simulations in COMSOL Multiphysics simulation software were performed for the subcatchment model (L/B = 1; F = 2.25 $m^2$; $i_x$= $i_y$ = 0.01; $\omega_{м}$ = 25 $cm^2$, which corresponds to the area of the natural small grate inlet type DM-1). The discharge of the flow via the subcatchment was $q_{d.m}$ – 1660 l/(s×ha); $t_d$ = 60 s. During the simulations was obtained numerical model of the flow with all parameters. The main aim of the research is to compare the runoff hydrographs from the model subcatchment (for $q_{d.m}$ = 1660 l/(s×ha) and $t_r$ = 60 s) obtained by: non-linear reservoir method; sector method; 3D sector method; from the experiment; by computer modeling by using *k–w* turbulence modules from COMSOL Multiphysics simulation software.

The results of the research: experimental and computer simulations are represented in figure 5.

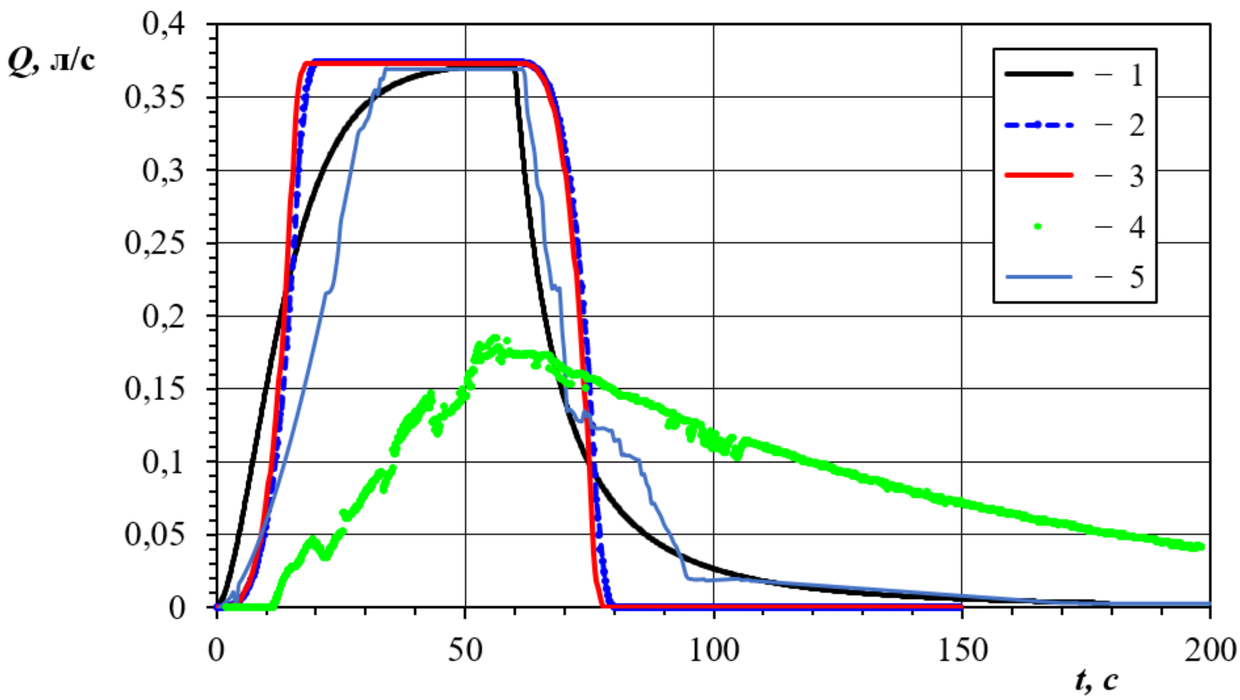


Fig. 5 Runoff hydrographs from the model subcatchment runoff (L/B = 1; F = 2.25 m$^2$; $i_x = i_y = 0.01$; $\omega_м = 25$ cm$^2$, which corresponds to the area of the natural small grate inlet type DM-1 at $C_L = 20$ for $q_{d.m} = 1660$ l/(s×ha) $t_d = 60$ s obtained by: 1 – non-linear reservoir method; 2 – sector method; 3 – 3D sector method; 4 – as a result of the experiment; 5 – by computer modeling by using *k–w* turbulence modules from COMSOL Multiphysics simulation software.

An experimental installation was designed and developed, on which was performed a set of experiments which allow experimentally model stormwater hydrographs from typical square in terms of subcatchments runoff in the range of values of the geometric scale $C_L$ = 10 – 30, which corresponds to full-scale sub-catchments with sizes from 15 × 15 m to 45 × 45 m. The design of the experimental installation allows to model the runoff hydrographs from flat subcatchments for various high schemes configurations with values of longitudinal and transverse slopes from 0.005 to 0.02. The methods of experimental research and processing of experimental data substantiated in work provide a relative error of definition of the peak discharge less than 0,48 %.

An improved three-dimensional sector method has been substantiated and developed, which allows to consider the actual configuration and height scheme of urbanized subcatchment runoff by automatically determining slopes for each sector based on data processing on three geodetic coordinates of all characteristic points of the subcatchment. The advantage of the three-dimensional sector method over the simple sector method is to consider the variable slope of the surface to the stormwater for subcatchments with a flat surface.

Considering in the 3D sector method the variable slope of an urban sub-catchment surface, depending on the location of the sector, causes significant changes in runoff hydrographs: reduction of surface concentration time by 13.7 % and increase in peak discharge by 11.3 % compared to the traditional sector method. Compared to the nonlinear reservoir method, the 3D sector method gives a peak discharge higher by 43.8 %.

A mathematical model of regulatory influence on stormwater hydrograph of capacitive elements of stormwater drainage systems − from conventional sewage wells to special control stormwater storage tanks (SWST) has been developed. An appropriate numerical algorithm and computer application have been developed to solve the direct and inverse problems of hydraulic modeling: to determine the required volume of capacitive elements at given limit parameters of stormwater runoff hydrographs in given cross sections or to determine runoff hydrograph parameters at given characteristics upper regulatory structures.