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Modelling of Hydraulics and Pollutants Transport in Sewer Systems

With Exemplary Calculations in SWMM

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Notation

Latin letters

- A – stream cross sectional area (m^2),
 A_c – surface of chamber (m^2),
 A_p – coefficient depended on the probability of rain occurrence and the average annual amount of precipitation ($\text{dm}^3 \text{ min}^{0.67} \text{ s}^{-1} \text{ ha}^{-1}$),
 A_S – subcatchment area per junction (ha),
 a_e – empirical exponent (-),
 a_i – constant of infiltration intensity (s^{-1}),
 B – width of the sewage table (m),
 C – mean concentration (kg m^{-3}),
 C_{CH} – Chezy empirical roughness coefficient ($\text{m}^{1/2} \text{ s}^{-1}$),
 C_r – frequency (repetition) of rain occurrence with intensity q (years),
 c – concentration (kg m^{-3}),
 D – inner pipe diameter (m),
 D_c – maximum wastewater depth in connection (m),
 D_z – equivalent diameter of the conduit (m),
 D^D – coefficient of longitudinal mass dispersion ($\text{m}^2 \text{ s}^{-1}$),
 D^M – molecular diffusion coefficient ($\text{m}^2 \text{ s}^{-1}$),
 D^M – molecular diffusion tensor,
 d_{50} – diameter of particles, accounting for 50% of mass for the smaller ones (m),
 d_p – maximum depression storage (m),
 d – depth of water over the subcatchment (m),
 E – total energy head (energy line) (m),
 E_k – kinetic energy head (m),
 E_p – potential energy head (m),
 E_j – ordinate of junction bottom that receives inflow, or ordinate of groundwater surface that has to be reached that groundwater flow occurs (m),
 Fr – Froude number (-),
 F – catchment area (ha),
 F_i – total value of infiltration at a given time (m),
 F_s – total value of infiltration needed to saturate the catchment (m),
 F_x, F_y, F_z – components of the vector of mass forces in directions x, y, z (m s^{-2}),
 f – friction factor (-),
 f_p – amount of water infiltrating into the ground (m s^{-1}),
 f_∞ – maximum or minimum f_p value in time equal infinity (m s^{-1}),
 f_0 – maximum or initial infiltration (m s^{-1}),
 g – acceleration of gravity (m s^{-2}),
 H – mean depth of the stream (m),

- H_n – height of normal precipitation (mm),
 H_a – the average annual amount of precipitation (mm),
 H_{gw} – ordinate of groundwater (m),
 h – local depth (m),
 h_c – chamber depth (m),
 h_{kr} – critical depth (m),
 h_z – height of sewage surface above the reference level (m),
 I – rainfall intensity (mm min^{-1}),
 i – precipitation intensity (m s^{-1})
 IMD – initial moisture deficit (m m^{-1}),
 K_s – saturated hydraulic conductivity of soil (m s^{-1}),
 k – coefficient of equivalent sand roughness (m),
 k^* – dimensionless coefficient of surface roughness (-),
 L – load (kg d^{-1}),
 L_c – connection length (m),
 L_o – overflow length (m),
 M – Manning-Strickler coefficient ($\text{m}^{1/3} \text{s}^{-1}$),
 m – mass of the analysed substance (kg),
 m_u – relation of maximum cross section velocity to the mean velocity (-),
 N – normal force (kg m s^{-2}),
 n – factor depending on the decrease and shape of the catchment (-),
 \mathbf{n} – normal vector to surface σ ,
 n_c – Manning's roughness of catchment (-),
 n_M – roughness coefficient acc. to Manning ($\text{s m}^{-1/3}$),
 O_z – the peripheral length of contact between transported sewage and pipe material (m),
 P – hydrodynamic pressure force (kg m s^{-2}),
 p – pressure (Pa),
 p_a – atmospheric pressure (Pa),
 p_r – precipitation (rain) probability (%),
 Q – volumetric flow rate ($\text{m}^3 \text{s}^{-1}$),
 Q_s – surface runoff ($\text{m}^3 \text{s}^{-1}$),
 Q_{gw} – groundwater flow intensity ($\text{m}^3 \text{ha}^{-1}$),
 Q_{op} – amount of precipitation on given area ($\text{dm}^3 \text{s}^{-1}$),
 Q_{sp} – amount of runoff from the given area ($\text{dm}^3 \text{s}^{-1}$),
 q – mass flow over the limiting surface σ ($\text{kg m}^{-2} \text{s}^{-1}$),
 q – unit rainfall intensity ($\text{dm}^3 \text{s}^{-1} \text{ha}^{-1}$),
 q_i – individual intensity of rain ($\text{dm}^3 \text{s}^{-1} \text{ha}^{-1}$),
 Re – dimensionless Reynolds number (-),
 R_h – hydraulic radius (m),
 S – friction slope (m m^{-1}),

S_e – energy line slope (-),
 S_s – subcatchment slope (m m^{-1}),
 S_c – average capillary suction from the soaked ground ($\text{m H}_2\text{O}$),
 s – slope of the channel bottom (-),
 s_{kr} – critical slope of the channel bottom (-),
 T – friction force (kg m s^{-2}),
 t – time (s), (min), (h), (d),
 U – mean flow velocity (m s^{-1}),
 U_* – dynamic velocity (m s^{-1}),
 u – local velocity (m s^{-1}),
 u_b – bottom velocity (m s^{-1}),
 u_{kr} – critical velocity (m s^{-1}),
 V – volume of the liquid (m^3),
 W – component of the vector of air velocity acting along the conduit (m s^{-1}),
 W_c – catchment width (m),
 x, y, z – spatial coordinates (m),
 z_d – height of the bottom above the assumed datum level (m),
 Z – gravitational force component (kg m s^{-2}),

Greek letters

α – Coriolis coefficient (-),
 β – dimensionless velocity coefficient (-),
 Δ – Laplace operator,
 Δt – calculations time step (s),
 ΔH_{max} – maximum change of wastewater level for time interval (m),
 δ – internal source density (the so-called source element) ($\text{kg m}^{-2} \text{s}^{-1}$),
 ε – velocity distribution factor (-),
 η – coefficient of dynamic (physical) viscosity (Pa s),
 η^T – coefficient of turbulent viscosity (Pa s),
 η^D – coefficient of dispersive transfer of momentum in direction x (-),
 λ – dimensionless coefficient of friction factor (-),
 ν – kinematic viscosity ($\text{m}^2 \text{s}^{-1}$),
 ρ – density (kg m^{-3}),
 τ – shear stresses at the conduit walls and wastewater interface (N m^{-2}),
 φ – runoff delay factor (-),
 ψ – runoff factor (-),
 Φ – advective mass flow ($\text{kg m}^{-2} \text{s}^{-1}$),
 Φ_x – diffusion flux relative to the x -axis ($\text{kg m}^{-2} \text{s}^{-1}$).

Introduction

The authors intended this study to be a set of systematized information and examples of the use of numerical models to describe wastewater flow and transport of pollutants in sewer systems. Definitions and mathematical models describing sewer systems functioning presented in the first part forms the base for the development of appropriate computer models. Simulations of both hydraulic conditions existing in the analysed system and qualitative analyses concerning transported pollutants are possible via presented models.

Besides the issues directly related to the construction of the model and simulations of sewer systems functioning, issues connected with the concept of the model, its calibration and computer simulations, were also touched upon in this book.

According to encyclopaedic definition, model is a physical system (physical model) or mathematical description (mathematical model) with some characteristics similar to some distinguished properties of real object. Modelling, however, is a method for studying various phenomena and processes or solving mathematical problems on the basis of properly formulated models.

In practical application in environmental engineering, among the others, the following mathematical models occur:

- dispersion of solid, liquid and gaseous pollutants in water environment – flow in non-pressurised systems (gravitational sewer system, rivers and streams, storage reservoirs) and pressurised (pressure sewer and water supply systems),
- removal of pollutants contained in wastewater via appropriate equipment and technological processes of wastewater treatment plant,
- flow of water and contaminants in porous media – e.g. soil profiles,
- spread of pollutants in liquid or solid form in the air.

The above exemplar application of mathematical model in environmental engineering, in the broad sense, reveals that modelling can be regarded as an important element in designing of the engineering structures and may be significant in the management of complex environmental systems. Application of various types of mathematical models in engineering practice allows to control real system, as well as to analyse its behaviour in various, often changing, conditions. Thus, modern engineer working in today's IT-enabled labour market ought to be familiar with general rules of conducting experiments with numerical models. He should also be familiar with the appropriate computer tools supporting engineers' works with creating technical documentation, testing, and analysing variants of completed projects, as well as exploitative works support.

According to branch literature, modelling can greatly facilitate, eg. sewer system exploitation due to the possibility to indicate areas with high probability of silting occurrence, or places with the opposite problem – occurrence of too high

flow rates leading to the damage of the channel bottom. In the first case, it is possible to assess possibility and profitability of sewer system rinsing, and in the case of cost-effectiveness, to choose appropriate schemes of flushing. Using computer models makes also possible identifying places exposed to wastewater rising, which threaten of flooding property or lower areas. Using the mentioned models, it is possible to estimate the effects of changes taking place in wastewater flowing into treatment plant in sewer systems or drained directly in storm overflows to the receiver. The use of numerical modelling significantly reduces cost of sewer systems managing, and in many cases, shortens process of planning, eliminating onerous field research. Moreover, through possible multi variants, modelling facilitates the decision on the scope of exploitation of the analysed system.

Presented elaboration consists of two basic parts: theoretical introduction and practical examples of the computer software using for modelling the sewer system work. The first part of the study provides an overview of the most important issues related to the modelling of hydraulic parameters of sewer systems, and the modelling of pollutants transport in these systems. The individual chapters contain rules of selections, construction and use of mathematical models relevant to describe phenomena occurring in sewer systems, in terms of quality and quantity.

More specifically were discussed issues related to:

- characteristics of the modelled object – sewer system (definitions of necessary input data related to the characteristics of sewer systems elements and materials from which they are made, and properties of pollutants transported in wastewater in the form of solution and sediments),
- hydrodynamics of modelled system (theoretical basis and practical aspects of modelling flows with free surface, equations of maintenance of momentum and mass, Saint-Venant equation, simplified equations for the flow),
- description of advective-dispersive pollutants transport in wastewater,
- methods describing sediments transport,
- selected numerical methods that can be used in computer modelling.

In addition to presented basic definitions of modelling flow parameter and contaminants transport in sewer systems, the study contains general description of SWMM 5.0 program and examples of its application to modelling the abovementioned processes. Because of that this book will refer to proper chapters, tables and figures of SWMM 5.0 User's Manual wherever it is necessary. The authors at the very beginning assume that the reader is familiar with basis of designing and sewer systems exploitation – sanitary and storm water as well as the combined ones – and mastered a basic ability to solve problems of water and pollutants transport in these systems.

1 General characteristics of sewer system

1.1 Sewer system history

More than five thousand years ago, the first hydro-technical structure functioning as a sewer system was built. It was rather a storm water system than a combined sewer system. Those times were followed by periods in which the important role of this kind of buildings in human material culture was perceived, as well as by those in which their importance was not appreciated. For a more complete introduction and description of the changes occurring in the way of perceiving the processes taking place in gravitational sewer systems it is desirable to approximate its origins and the subsequent development stages (www.sewerhistory.org).

The first discovered constructions, performing the role of sewer system, built by humans, are dated back to about 3000 BC. They are located in Habuba-al-Kariba near the Assad Dam in the area of today's Syria. As main collectors, pipes with rectangular section were applied, while as side ones, lesser round pipes. The system consisting of them functioned mainly as a storm water system (drainage system) rather than a combined one. On the grounds of the former Babylonia (2500 – 500 BC), developed sewer systems equipped with rain grooves made of fired ceramic pipes were also in existence (e.g. Temple of Bel, Nippur, Babylonia dating back to more than 2500 years BC). Other well-known examples of ancient sewer systems are objects in the Palace of Knossos on Crete, and also in Greek cities (e.g. gymnasium in Amphylopolis of about 430 BC or in the ancient Dion – about 600 BC, in the area of today's Macedonia), as well as the Cloaca Maxima – a sewage canal of ancient Rome which has been created after building-up open channel transporting sanitary sewage and storm waters (*Huisman, 2001; Angelakis et al., 2005*).

After the collapse of the Roman Empire, the ancient sanitary knowledge was lost for many centuries. Nevertheless, in many cities of medieval Europe rainwater, along with domestic sewage, were flowing in open gutters, instead of built-up sewer systems. It was the eighteenth century, when the authorities of modern European countries begun to develop sewer systems in big cities of those days – Paris and London. Such actions were enforced mainly by hygienic problems (outbreaks of great infectious diseases), and by the need to drain periodically accumulated storm water (*Ashley et al., 1999*). Therefore, commonly believed opinion that there were sanitary engineers who saved more lives than the doctors of that time did by inventions such as flush toilets, siphon closing, and build-up sewer system, limiting the spread of diseases of a digestive system, seems to be correct. The inventions of previous centuries led the development of sewer system to the current form which, in the light of current knowledge, function not only as a 'simple tool' of sewage

hydraulic transport, but also as a biological reactor, inside which a large number of various processes occur (*Pomeroy and Parkhurst, 1972; Koch and Zandi, 1973; Green et al., 1985; Nielsen et al., 1992; Stelmach et al., 1995; Garsdal et al., 1995; Ashley et al., 1999; Huisman, 2001; Hvitved-Jacobsen et al., 1998; Hvitved-Jacobsen, 2002; Abdul-Talib et al., 2003; Myszograj, 2005, 2006; Łagód et al., 2010*).

1.2 Sewage as a dynamic system

Sewer systems (understood in general as systems of conduits carrying sanitary sewage, general drainage and rainwater) are complex systems within which changes occur not only with distance but also with time. The abovementioned changes appear in a rhythm of irregularity of sewage outfall (daily, weekly, yearly), and because of storm and random water infiltration (*Błaszczuk et al., 1983; Stelmach et al., 1995; Imhoff and Imhoff, 1996; Huisman, 2001; Dąbrowski, 2004; Łagód et al., 2010*). All mentioned processes of transport and biodegradation occur in all types of sewer systems, but are the most visible and important in relation to the sanitary sewers and less to the combined sewers and storm water systems.

Sewer systems (all types of sewer systems) understood as dynamic systems can be divided into the following, interrelated components: the static part – construction of sewers, and the dynamic one – wastewater with heterotrophic organisms biomass suspended in its depth, biological membrane (biofilm) covering the walls of pipes, sewer sludge and air occupying the space over the free surface of wastewater.

Dependencies existing between presented components (Fig. 1.1) are formed by the following factors:

- The physical properties of the static elements of sewer system – they are the shape and dimensions of pipes, slope of pipe bottom, the roughness of the wall.
- Hydrodynamic properties of the system – shaped by the volume of wastewater flowing stream which is affected by irregularity of water demand, and the presence of random and infiltrated waters in separate sanitary sewer system and also by the amount of precipitation in combined sewer system and storm water system.
- Environmental conditions – parameters like temperature and pressure.
- Biological, chemical and physical processes in sewer system – these phenomena will be only scour concerned in this study.

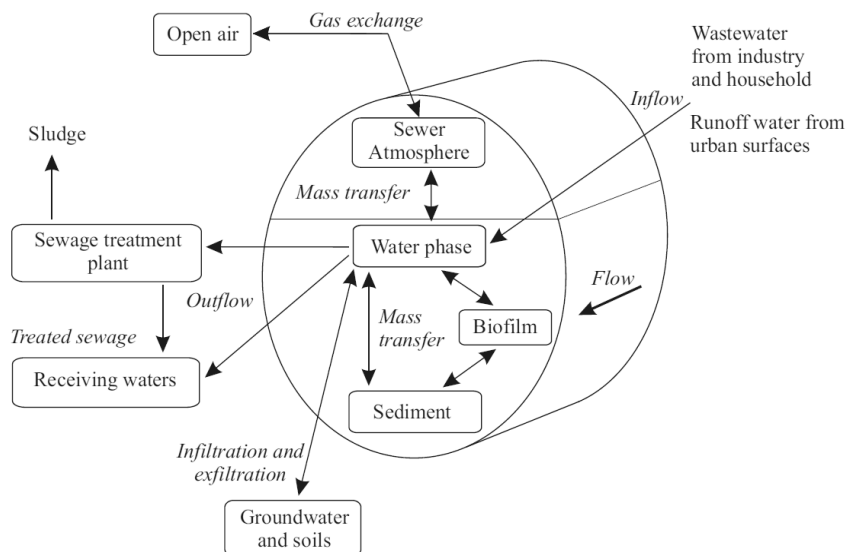


Fig. 1.1. Components of dynamic system in gravity sewer system and the connections between them, based on: (Ashley *et al.*, 1999; Hvitved-Jacobsen, 2002)

1.3 Selected elements of the sewer system and their impact on the transport and transformations of pollutants

Building the numerical model of dynamic system in gravitational sewer system collector (whether a storm water system, combined or sanitary sewer system), at the very beginning, the elements composing such a model must be isolated and described. Thus, mentioned elements will be characterized in detail in the further part of this work, and their role in transport, and pollutants transformation will also be presented.

1.3.1 Sewage flow in pipes of gravity sewer system

Gravity sewer system pipes are usually made as closed section pipes. Liquid flow inside them takes place in the case of incomplete filling of cross-section. Therefore, they are considered as channels with unpressurised flow and free surface.

Cross-sections of sewer system pipes can have different shapes depending on the type of sewer system and local conditions. Apart from circular cross-sections, there are also egg-shaped, bell-shaped, and pear-shaped ones. Sometimes trapezoidal or rectangular cross-sections are used (Mitosek, 1997). The SWMM 5.0 program supports all of mentioned above most popular canal shapes – more specific information are available at the SWMM 5.0 User's Manual – Table 3-1.

The assumption of constant wastewater flow, although true for the adopted computational sections, is rarely met in most sewer systems taken as a whole. In the real conditions, during the exploitation of the sewer system on a technical scale some changes in flow intensity occur, also as a result of ground water infiltration, or sewage exfiltration to the ground. The intensity of these processes depends largely on water relations in the ground in which the collector is placed. Variations of sewage flow intensity during twenty-four hour periods are affected also by inequality of water consumption within a settlement. Thus, in actual conditions, wastewater flow in sewer conduits occurs with varying intensity both in time and on the length of the sewer system in question.

The assumption on constant slope of the channel bottom, as well as constant cross-section and dimensions between points of junction (nodal point), is close to true conditions. However, their realization depends mainly on the accuracy of construction work done, and on the quality of the materials used.

Local resistances (due to friction and/or hydraulic resistance) occurring in sewer system can be considered in several ways. They can be taken into account by assuming an appropriate roughness factor, introducing correcting substitute lengths, or – difficult to apply in practice – detailed calculations of real objects. In engineering practice, the first method is often adopted due to the availability of existing theoretical studies (*Walden and Stasiak, 1971; Sawicki, 1998; Orzechowski et al., 2001; Dąbrowski, 2004*), their experimental verification and widely applied methods, as far as sewer systems are concerned.

The adoption of previously mentioned assumptions – constant flow intensity between points of junction, dimensions, drop of bottom/slope, and channel roughness leads to the situation in which the existence of uniform motion is assumed. It is a basic assumption made in the calculations of hydraulic sewage channels for design purposes. With this kind of movement, total energy line, piezometric pressure line, wastewater surface, and channel bottom are parallel to each other. Moreover, piezometric pressure line and sewage surface coincide. In this case, the slope of all mentioned lines is identical and equal to hydraulic decrease, that is, the ratio of height loss caused by frictions to the conduit length (*Błaszczuk et al., 1983*).

Calculations of sewer pipes parameters based on uniform motion are sufficiently accurate in engineering practice (*Błaszczuk, 1965; Błaszczuk et al., 1983; Imhoff and Imhoff, 1996; Heidrich, 1999; Suligowski, 2000; Płuciennik and Wilbik, 2003*). The above assumption is insufficient in detailed calculations to determine the filling of the channel with sewage on defined length, and linking the flow velocity with it. In such cases, in order to provide adequately accurate input data for numerical simulations and to do the verifying calculations useful in the exploitation of sewer system, it is assumed that nonuniform motion appears in the channel.

1.3.2 Characteristics of storm water runoff

It is difficult to qualitatively assess storm water runoffs, although they can be characterised by specifying, for specific cases, the content of various groups of contaminants. These groups include (Ociepa, 2011; Bąk *et al.*, 2012; Królikowska and Królikowski, 2012):

- settling and unsetting suspension, as well as bigger solids particles,
- inorganic substances,
- organic matter,
- living organisms, especially pathogens, bacteria and viruses, protozoa, and small tissue organisms.

The composition of polluting substances resulting from storm water runoffs and contaminants occurring in them are typical for given catchment and atmospheric precipitation. Proper and accurate storm water runoff assessment can only be made based on the results of direct testing cycle of runoffs from a specific catchment. They are reliable only for the catchment and for the case of given parameters range (Park *et al.*, 2009; Ociepa, 2011).

The load of contaminants present in this type of sewage is often compared to those from municipal wastewater. In dependence on the contaminants rate, the ratio of annual contaminants load carried with storm water runoffs to those in raw municipal wastewater varies from a few to several percent (Soonthornnonda and Christensen, 2008). This is a consequence of phenomenon specificity of storm water runoff to the catchments. Total annual flow of storm water runoff is less than domestic sewage. This proportion is reversed with reference to instantaneous flow intensities.

The composition of storm water runoffs can be described using similar indicators as in the case of municipal wastewater. In that case, the following are taken into account (Bąk *et al.*, 2012; Królikowska and Królikowski, 2012):

- concentration of total suspension/total suspended solids – TSS,
- biochemical oxygen demand – BOD,
- chemical oxygen demand – COD,
- concentration of biogenic substances,
- concentration of heavy metals,
- concentration of chlorides,
- concentration of petroleum derivative substances.

Suspension concentration is the most significant factor of sewage contaminants caused by atmospheric precipitations. The problem is constituted primarily by contaminants associated with suspension, such as organic compounds, heavy metals, bacteria and viruses (Tab. 1.1). Additionally, a significant share of oil contaminants and the phenomena occurring on the surface of suspensions complicate the issue

(Ociepa *et al.*, 2010; Bąk *et al.*, 2012). They are for instance: ion exchange, catalysis involving enzymes and mineral catalysts. In storm water runoffs mineral suspension is a predominating element. Organic suspension, on the other hand, occurs in catchments like market places, green areas, especially in the autumn as a result of falling leaves. Size distribution of particles appearing in storm water of urbanised areas is distinguished by high changeability and it constitutes an individual characteristic of a catchment. In most of the analyses, it is concluded that the largest share is that of particles in the range of 10–300µm.

Table 1.1. Contaminants accumulated in suspension (Królikowska and Królikowski, 2012)

Contaminants	Percentage of contaminants associated with the suspension
COD	83–92%
BOD	90–95%
Total Nitrogen	65–80%
Hydrocarbons	82–99%
Lead	97–99%

The suspension concentration in storm water runoff varies significantly and often exceeds values typical for sanitary sewage. It depends on the catchment management, type and degree of surface sealing, traffic intensity, precipitation parameters, and the number of rainless days before the precipitation, and also on the sewer exploitation (Park *et al.*, 2009; Bąk *et al.*, 2012). A high concentration is observed in the run-offs of disordered catchments in which substrate erosion from unsealed surface occurs. During a downpour, runoff water grabs even the heaviest suspension fractions with high weight, which allows their easy sedimentation. Over the duration of precipitation, the suspension's share in storm water runoff decreases. The share of the organic suspension increases in the case of green catchments in autumn. This takes place due to the presence of leaves and other dead parts of plants.

Significant concentration of suspension appears also in snowmelt runoff and often exceeds its concentration in storm water runoffs (Bąk *et al.*, 2012). This kind of suspension is a mineral one, especially when, apart from chemical substances (usually chlorines), sand and other mineral aggregates are used to prevent the formation of glazed frost (Ociepa *et al.*, 2010). In this case, for the most part the suspension is combined with various kinds of organic and inorganic contaminants.

The individual size of suspension fractions is significant in the transport of contaminants integrated with it. The smallest fractions contain the highest contaminants percentage, as they have the most developed surface, which has an impact on sorption properties of molecules (Tab. 1.2).

Table 1.2. Contaminants percentage associated with individual fractions of suspensions in storm water runoffs (*Królikowska and Królikowski, 2012*)

Total suspended solid value	Percentage of total suspended solid	Contaminants percentage associated with individual fractions of suspensions			
		COD	BOD	Total Nitrogen	Lead
> 250 μm	11–40	30	25	13	41
50–250 μm	6	0	9	3	41
10–50 μm	10–20	12	14	11	3
< 10 μm	45–63	58	52	73	56

The value of biochemical oxygen demand (BOD) in storm water is usually low, and often does not reflect the actual number of organic compounds. This is because biochemical processes are usually hampered by toxic substances and inhibitors present in described sewage (*Dąbrowski, 2004*).

In the runoffs from roads, car parks and manoeuvring areas, BOD is not a good indicator to determine the qualitative characteristics of storm water runoffs (*Dąbrowski, 2004*). Because of these reasons and due to the presence of petroleum derivatives in storm water, the COD indicator is much more convenient (Tab. 1.3).

Table 1.3. Approximate contaminants concentration in storm water runoffs (*Królikowska and Królikowski, 2012*)

Contaminants indicators	Contaminants values in storm water runoffs	
	Minimum and maximum values	Average values range
Total suspended solids (g m^{-3})	5–40 000	80–17 000
BOD (g m^{-3})	1–1100	7–83
COD (g m^{-3})	5–3100	40–50
Chlorines (g m^{-3})	5–428	12
Total nitrogen (g m^{-3})	0.3–12.7	3–10
Lead (g m^{-3})	0.9–12.6	-
pH	3.9–8.7	5–8

Chemical oxygen demand (COD), defined as the amount of oxidised substances in a chemical way, usually characterises the degree of storm water runoffs contamination quite well. Moreover, there often occur dependencies between COD

value and the concentration of other contaminations, such as heavy metals. COD value varies from several tens to even several thousand mg dm^{-3} , and often exceeds the value of 150 mg dm^{-3} (Ociepa *et al.*, 2010). COD and its fractions have been characterised in detail in the subsection concerning sanitary sewage parameters.

In storm water runoffs the concentration of heavy metals is also significant, mainly due to the possible presence of lead. Nevertheless, since the introduction of the use of unleaded petrol on a wider scale, the problem in Poland and European Union is now less important than in previous times. Heavy metals are mainly present in the runoffs of storm water from traffic routes, and areas heavily urbanised and industrialised (Rybicki and Rybicki 2001; Bąk *et al.*, 2012;). They come from unburned fuel fractions, wear of tires and asphalt. In most cases they are toxic and carcinogenic compounds. Heavy metals may be present in sewage as dissolved salts, ions or insoluble compounds (Królikowska and Królikowski, 2012).

Chlorides occur generally in snowmelt runoffs as a result of using chemicals to fight glazed frost. These are mixtures of NaCl, CaCl₂, and sometimes MgCl₂.

Petroleum derivatives present in storm water runoffs are all organic substances from using and processing of crude oil. They are present in sewage in dissolved form, as an emulsion, or in suspension. Storm water runoffs can also be contaminated with aromatic hydrocarbons, derived from unburned fuel fractions or remained as products of tyre wear and asphalt surface. Higher concentration of petroleum derivatives and oils in storm water runoffs outside petrol stations may be the result of accidents and road disasters, and also of the use of faulty seals in drive mechanisms, or of hydraulic leaks in motor vehicles.

The pH of storm water runoffs is usually neutral. However, while rain has contact with air containing carbon dioxide and other acidic substances with clearly increased participation within many urban areas, precipitation pH value decreases below 7 (Ociepa, 2011). In turn, on the catchment surface alkaline substances may occur. Thus, pH of storm water runoffs flow can be in the range of 5–8, and sometimes even 9.

Also range of most important pollutants indicator values (concentration) characterising urban runoff water quality are given in SWMM 5.0 Manual – Appendix A.9.

1.3.3 Municipal sewage in sanitary sewer system

The composition of so-called “fresh” sewage, the age of which is dated in minutes, or at most a few hours, is often different from the composition of wastewater exposed to technological processes in sewage treatment devices (Roman, 1986; Imhoff and Imhoff, 1996; Huisman, 2001). The differences in wastewater composition are triggered to a large extent by the processes of contaminants’ transformation that occur during the transport in sewer system, which can last even more than 20 hours (Huisman, 2001; Hvitved-Jacobsen, 2002; Abdul-Talib *et al.*, 2003;

Myszograj, 2005; Krajewski and Niedzielski, 2005, 2005a; Łagód et al., 2010). Heterotrophic biomass, which is also a processing factor resulting in enzymatic hydrolysis of suspension macromolecules, is also floated in wastewater stream.

Wastewater flowing in sanitary sewers is generated as a result of the use of water, in industrial processes as well as for residential purposes, and in storm water/drainage system also because of the necessity to discharge storm water from urbanized area (*Błaszczuk et al., 1983; Imhoff and Imhoff, 1996*). The composition of municipal wastewater is thus determined by mixing in: domestic sewage, sometimes industrial wastewater, random and infiltrated waters at different proportions. As far as the combined sewer system is concerned, apart from the abovementioned, there is rainwater, and also water from melting snow, ice and snow mud. It can be concluded that wastewater composition will be dependent on the structure and size of a given settlement unit, as well as on the technical condition of the sewer system determining the intensity of infiltration and exfiltration.

Generally, wastewater originated from human population (domestic sewage) has a complex composition, and contains organic and inorganic contaminants having different sizes – table 1.4 (*Andoh and Smisson, 1996; Huisman, 2001; Hvitved-Jacobsen, 2002; Krajewski and Niedzielski, 2005*). Municipal wastewater contains on average about 60% of organic matter and 40% of dissolved and non-dissolved inorganic matter. Among the organic compounds, predominant are proteins participation of which may vary from 40–60%, and carbohydrates present in amounts from 25 to 50%. The content of fat is about 10% (*Klimiuk and Łebkowska, 2005*). The biomass of saprotrophic organisms, as well as a number of other compounds present in much smaller concentrations, also float in wastewater stream.

Table 1.4. The composition of wastewater presented as a percentage share of each group of organic compounds in the total COD (Chemical Oxygen Demand) and TOC (Total Organic Carbon) (*Krajewski and Niedzielski, 2005*)

Index/component	Characteristic fractions			
	Dissolved	Colloidal	Over colloidal	Sedimenting
Size (µm)	< 0.08	0.08–1.0	1–100	> 100
COD (% COD _{Tot})	25	15	26	34
TOC (% TOC _{Tot})	31	14	24	31
Organic components in the total percentage share				
Fats	12	51	24	19
Proteins	4	25	45	25
Carbohydrates	58	7	11	24

The composition of municipal wastewater has been investigated many times in the past. As a result of that research, the content of major components such as fats, carbohydrates, proteins, organic acids has been defined (Nielsen *et al.*, 1992; Sophonsiri and Morgenroth, 2004), as well as other chemical substances. The level of selected indicators of contaminants has been also investigated (Butler *et al.*, 1995; Orhon *et al.*, 1997; Sophonsiri and Morgenroth, 2004).

Impact of infiltrated water on the wastewater composition is usually revealed in its dilution, and less in biogenic elements' concentration increase. However, that takes place when infiltrated water comes from run-off from heavily fertilized agricultural areas. In some cases, infiltration can also lead to a temperature change – usually its reduction.

Taking into account the above, it can be concluded that not only the structure of settlement (residents and industrial wastewater), but also daily and seasonal variability of temperature, as well as wastewater retention time in sewer system have a significant impact on the quality of wastewater flowing to the treatment plant (Nielsen *et al.*, 1992; Stelmach *et al.*, 1995; Huisman, 2001; Hvitved-Jacobsen, 2002; Abdul-Talib *et al.*, 2003; Łagód *et al.*, 2010).

However, as accurate a determination of wastewater composition as that presented in Table 1.4 is not widely used in the control of processes in technological objects of wastewater treatment plants, or in receivers – mainly rivers. This is due to the high costs, labour intensity, and little impact of such analysis on the final quality of the wastewater treatment processes, usually, it is enough to determine total COD, BOD₅, suspended solids, and forms of nitrogen and phosphorus.

1.3.4 Sediments and their transport in gravitational sewer systems

Sediments in gravitational sewer systems appear when the velocity of flow decreases below the value of hydraulic self-purification. They have a significant influence on the processes occurring in sewer systems as a cause of e.g. periodical fluctuation of pollution loads entering wastewater treatment plants. Sediments deposited during the phase of low canal filling and low flow velocity reduce the pollutant load, thus during the phase of high filling and high flow velocity the deposited pollutants are washed away, thereby rapidly increasing the concentrations and loads of transported pollutants. This phenomenon directly influences the pollutant load entering the wastewater treatment plant or storm spillway and the sewage discharge receiver. Sediments deposited in the channel also cause changes in the pipe cross-section shape and thus bring about changes in the physical and hydrodynamic parameters of the entire system (Crabtree, 1988; McGregor *et al.*, 1993; Ackers *et al.*, 1996; Hvitved-Jacobsen, 2002; Dąbrowski, 2004; Jilali *et al.*, 2008). Sediments also contribute to development of sulphuric corrosion of pipes and have an impact on the intensity of biological biodegradation of wastewater in sewer conduits.

The techniques of sampling and measurements applied currently yield results that only partially reflect the properties of sediments in their natural environment.

The reological properties are influenced by accumulation of sediments just beneath the wastewater surface. This may be one of the major reasons for the increased resistance of sediments to the shear stress observed in laboratory conditions. Investigations of the properties of sewer sediments are usually carried out in order to obtain knowledge about the level of pollutant release and description of reologic properties, particularly the shear stress, which determines sediment erosion.

Since studies concerning wastewater sediments and related processes are relatively expensive, they are only conducted in countries in which the bidding law requires mathematical modelling of mass transport to wastewater plants and storm spillways (*Dąbrowski, 2004; Łagód et al., 2010*). The results of this research provide data necessary to calibration of hydraulic models.

Classification of sediment forms in sewer systems

The following classification of sediments is used in EU (*Crabtree, 1988; Hvitved-Jacobsen, 2002*):

A – non-organic and non-cohesive sediments,

B – sediments with the A-type non-organic structure but agglomerated by oil derivatives and characterized by cohesive properties,

C – organic sediments, moving over the surface of sediments A and B with lower velocity than flowing sewages,

D – biofilm developed on pipe walls,

E – sediments in storage tanks.

Additionally, two other groups of sediments are sometimes distinguished (*Dąbrowski, 2004*):

F – storm conduit sediments,

G – pressure pipe sediments (after pressure sewer attachment).

Sediments A and B are the major types found in wastewater systems, thus, they exhibit the highest load of COD accumulated, although the concentration of pollutants in these sediments is lower than in the case of type C.

The highest content of organic pollutants has been noted in sediments from group C, in which the COD content reaches the level of up to several hundred (even 300–500 gO₂dm⁻³). These sediments move over the surface of group A and B during the phase of low sewage flow in a wastewater pipe. The presence of sediments C and D in sewer systems results in occurrence of biodegradation processes, because these sediments contain heterotrophic organisms, the process factor of the transformations mentioned.

Group D sediments comprise heterotrophic living organisms, therefore, the organic content in this group of sediments is high. The thickness of the layer formed by group D is usually low (generally not exceeding 2 mm) but the anaerobic conditions are possible. This, in turn, contributes to formation of hydrogen sulphide, which induces sulphuric corrosion of pipe surface, attacking subsequently the vault and side walls of the canal.

Group E sediments are characterized by a high degree of fragmentation, hence, the grain surface area in the unit volume of sewage is significant. This facilitates extensive adsorption of practically insoluble organic pollutants and heavy metals.

Group F sediments present in wastewater and storm systems are characterized by variable, time-dependent (seasonal) composition. In particular, they contain large amounts of leaves falling from trees during late autumn. Pressure pipe sediments (group G) commonly occur at the pipe slope and contain huge amounts of organic compounds, especially fats.

The general description of the structure and properties of sediments should be taken into account at the stage when minimal inclinations of conduits are designed. It is also very important in modelling the pollutant load transport in the sewer system and the process of wastewater biodegradation, since different models of transport should be used for different types and properties of sediments (*Dąbrowski, 2004*).

The sediments transported in the sewer are often the subject of physical and biochemical analysis and the proper way of sampling, for instance using a sediment trap installed at the bottom of pipes, is necessary to obtain credible results. The exemplary results of measurement are presented in Table 1.5.

Table 1.5. Characteristics of near-bed sediments inside egg-shaped conduits (1–1030x686 mm, 2 and 3–1780x1625 mm) (*Arthur and Ashley, 1997; Dąbrowski, 2004*)

No	Particle diameter d_{50} (mm)	Wet state density (kg m^{-3})	Volatile component (%)	Mean COD ($\text{gO}_2 \text{m}^{-3}$)	Mean BOD ₅ ($\text{gO}_2 \text{m}^{-3}$)	Mean flow rate ($\text{m}^3 \text{d}^{-1}$)
1	0.5–11.0	1143–1998	1.4–28.6	87522	28594	1900
2	0.5–4.0	1000–1066	31.8–68.1	214000	82758	6700
3	0.09–2.5	1000–1108	55.6–91.2	124246	96119	7500

Based on measurements including the mechanical properties of sediments, it was found that critical shear stresses τ_c depend on the density of analysed sediments in their natural environment (*Wotherspoon and Ashley, 1992*). Polish researches (*Dąbrowski, 2004*) have demonstrated that phenomena connected to sediment transport and pollutant release are largely dependent on the relations among the particular sediment properties, the most important of which include density, moisture, and porosity.

Sediment transport in the gravity sewer system

Proper exploitation of sewer systems requires providing conditions for self-purification of hydraulic conduits. Such requirements are fulfilled when the canal inclinations have been chosen properly. However, the economic conditions limit designing pipes that would eliminate deposition of any sediments ensuring transport thereof throughout the day. Therefore, the binding rules of sewer system design ensure periodical transport of the best part of sediments, maximal annual sewage flow rates, and effective channel ventilation (*Błaszczuk et al., 1983; Dąbrowski, 2004*). Thus, in the real conditions of sewer systems, sediments are periodically accumulated in the pipes and then washed away during the phases of a high wastewater flow rate.

Described at the literature studies show that the concentration of particles is non-uniform in the whole stream of flowing sewages and its value rapidly increases towards the pipe bottom (*Arthur and Ashley, 1997; Dąbrowski, 2004*). Since there is one more increase in the constant phase concentration connected with sediments deposited on the pipe bottom, the suspension transport in the layer placed between the two mentioned layers of constant phase densification is referred to as the near-bed transport (*Palarski, 1982*). It is associated with the occurrence of the turning, displacement, and saltation phenomena.

Data presented in engineering literature (*Błaszczuk et al., 1983; Imhoff and Imhoff, 1996*) suggest that, to obtain proper working conditions of the sewer system at the designing phase, it is necessary to allow for pipe inclinations that would yield the lowest velocity of channel self-purification. This notion is understood as a velocity that stops formation of a sediment bed at the canal bottom. It is also advisable that self-purification should occur even at the lowest flow and filling rates. The velocities mentioned are understood in two ways: as a non-silting velocity as well as a terminal velocity (*Sawicki, 1998*).

The convection velocity is a mean velocity in the active cross section at which all particles are being transported in the channel, partially in a suspended form and partially dragged near the bottom. In this case, the processes of sediment deposition and formation of sediment bed do not occur. This terminology is accepted in literature focused on the processes occurring in sewer systems; it originated in research concerning debris transport in rivers and other watercourses (*Dąbrowski, 2004; Sawicki, 1998*).

The terminal velocity is a mean velocity in the stream cross section that triggers the process of erosion of sediments deposited during the lowest filling of the canal. Laboratory investigations showed that uniform sediments are completely removed after a 10% increase in the flow velocity described (*May et al., 1996; Nalluri and Alvarez, 1992*). The literature sources do not present a universal value of required terminal velocity because its value depends on the sewage composition, type and shape of the sediment particles as well as the hydraulic radius value – the shape, geo-

metric characteristics, and filling of the sewer canal (Błaszczuk *et al.*, 1983; Nalluri and Ghani, 1996; Dąbrowski, 2004).

When mean velocities are used, it is assumed that the flow velocity is equal in all points of a given cross section. In reality, the flow velocity is different in every point and has the lowest values near the canal bottom, which is presented in figure 1.2.

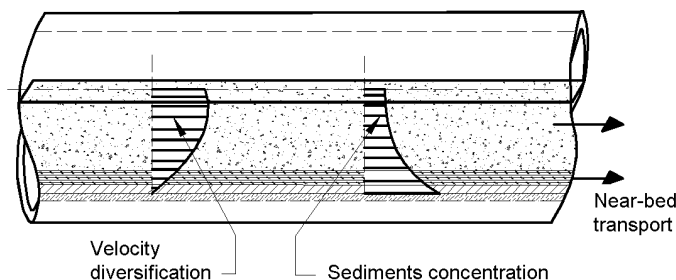


Fig. 1.2. Sediment transport in a sewer conduit – a constant sewage level, based on (McGregor *et al.*, 1993)

Maintenance of wastewater flow velocity at the level of 1 m s^{-1} , which seems to be the simplest method of designing, would result, in some cases, in too high inclination of pipes, leading to excessively high and economically unjustified pipe depression. However, the sewage flow velocity in sewer and storm canals should not be lower than 0.8 m s^{-1} during the phase of the maximum canal filling. In specific cases, where there is no possibility to ensure the self-purification velocity of flow, pipe flushing should be made possible.

The third value of the flow velocity that is essential in the sewer exploitation practice is connected with the beginning of erosion of the conduit side walls. To prevent the mechanical damage to the inner surface of pipes, the flow velocity should be lower than 3.0 m s^{-1} for concrete and ceramic pipes and 5.0 m s^{-1} for cast iron pipes. The maximum admissible velocity of sewage flow inside storm conduits equals 7.0 m s^{-1} (Błaszczuk *et al.*, 1983).

The recent approach to the problem of self-purification of sewer conduits is based on the shear stress method (Crabtree *et al.*, 1995). The values of shear stresses in the stationary flow may be derived from the formula for both the energy balance of sewage stream in the conduit and the balance of forces acting on the sewage stream (Dąbrowski, 2004). Below, there is a general formula for calculation the shear stress values:

$$\tau = \rho g R_h S_e \quad (1.1)$$

where: τ – shear stresses at the conduit walls and wastewater interface (N m^{-2}), ρ – wastewater density (kg m^{-3}), g – gravitational acceleration (m s^{-2}), R_h – hydraulic radius (m), S_e – energy line slope, in the stationary flow is equal to the canal inclination.

The value of shear stresses is important for biofilm development and erosion. Shear stresses between 3 and 4 N m⁻² usually prevent development of a biofilm on canal side walls. In conduits with a diameter lower than 0.4 m, such stresses arise at the wastewater flow velocity of approx. 1 m s⁻¹, for bigger diameters, the velocity should range between 1.2 and 1.4 m s⁻¹ (*Hvitved-Jacobsen, 2002*). In the case of maximum filling, inclinations that match the canal diameter D allow maintenance of shear stresses at the conduit walls- wastewater interface at the level of 2.5 N m⁻². These stresses do not decrease below that value as long as the relative filling of the sewer conduit is lower than a half of the cross section height (*Dąbrowski, 2004*).

The two methods mentioned above, based on the self-purification velocity and critical shear stress, allow for the achievement of the same objective, which is prevention of transported sediment deposition inside gravitational sewer conduits. This issue is particularly important due to the cohesive properties of transported sediments (*Crabtree et al., 1995; Berlamont and Torfs, 1996; Łagód et al., 2010*). The shear stress of about 1.8 N m⁻² is required to remove the layer of freshly deposited sediments, while the stress value of 800–1000 N m⁻² is necessary to remove the sediments after long-term pipe exploitation. To illustrate the scale of the problem, it is noteworthy that, during rainy weather, the values of shear stress of 20 N m⁻² were reported inside the pipes constructed with relatively high inclinations (apart from sewer systems in mountain regions). The inclination of sanitary conduits should ensure daily cyclical removal of deposited sediments occurring during the phase of the maximum flow rate. In the case of the storm systems, the required intensity of sediment removal should be attained during the rainfall event. If this condition is not fulfilled, only special methods of conduit rehabilitation may restore the hydraulic capacity of the pipe after several years of sanitary system exploitation.

The technical activities aiming at removal of deposited sediments are often extremely expensive, therefore, proper choice of the minimal conduit inclination contributing to the self-purification velocity (suitable values of shear stress) has become an important issue at the stage of sewer system design. Besides, sediments deposited at the canal bottom pose a serious threat for the receiver of storm spillway wastewater and constitute heterogeneous strain for wastewater treatment plants by pollutant loads.

Description of sediment transport in gravitational sewer systems

The hydraulic transport of solid particles inside the sewer systems may consist in floating by the sewage stream and dragging along the canal bottom. The movement of single A group sediment particle is induced by the forces of hydrodynamic pressure force. The component of gravitation force parallel the conduit bottom may be insufficient because the commonly used low conduits bottom angle of inclination. This situation may be graphically presented as shown in figure 1.3.

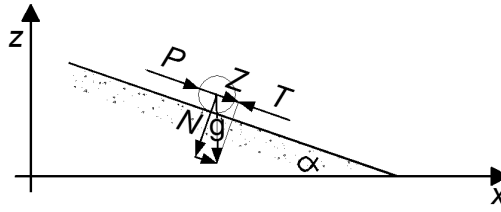


Fig. 1.3. Forces influencing the spheroid particle of group A at the bottom of a gravitational conduit (Błaszczuk *et al.*, 1983)

The particle presented in figure above is influenced by the following forces: P – hydrodynamic pressure force (kg m s^{-2}), Z – gravitational force component (kg m s^{-2}), T – friction force dependent on the friction factor and normal component of gravitational force $T=f N$ (kg m s^{-2}), N – normal force (kg m s^{-2}), while g – gravitational acceleration (m s^{-2}), f – friction factor (-). The inertial force and congruence of the particle to the bottom are neglected. The required mean sewage flow velocity, authoritative for the inorganic and incohesive sediment particle of diameter d (m) dragged along the bottom of a sewer pipe of diameter D (m), may be calculated with following equation:

$$U = \frac{u_b}{\varepsilon} \quad (1.2)$$

where: U – mean cross section velocity (m s^{-1}), u_b – bottom velocity (m s^{-1}), ε – velocity distribution factor (-).

The ε factor is described as:

$$\varepsilon = m_u - \frac{2}{3}(m_u - 1) \ln \frac{1,25D}{d} \quad (1.3)$$

where: m_u – relation of maximum cross section velocity to the mean velocity (-).

Sediments deposited inside sewer pipes should be taken into consideration while determining the capacity of old canals. The sediments settled inside sewer conduits affect the hydraulic resistance of flow in three different manners: by decreasing the inner cross section area, changing the roughness coefficient for pipe walls, and decreasing the flow energy caused by the work load during elution of deposited sediments.

The changes in the roughness coefficient value affecting flow resistance are difficult to predict because the surface of the sediments bed usually forms spatially different shapes, depending on the dimensionless Froude number. For $Fr < 0.2$ a smooth shape of sediment surface is the most probable, for $Fr=0.2-0.35$ and $Fr=0.35-0.6$ distinct ripples and dunes, respectively, were visible. Thereafter, re-smoothing of the sediment surface occurs for $Fr=0.6-1.0$ and anti-dunes appear for $Fr > 1.0$ (Dąbrowski, 2004).

2 Hydraulic and hydrological issues related to urban stormwater systems

2.1 Precipitation

Precipitation occurs mainly in the form of rain, snow and hail. In general, rainfall is characterized by 3 parameters: rainfall intensity $I = \Delta h / \Delta t$ (changes of precipitation height Δh in time Δt), rain duration t and territorial range F . The intensity of the rain is not constant throughout its duration as well as in the space covered by precipitation. In sewer systems, as the concept of individual unit rainfall intensity q ($\text{dm}^3 \text{s}^{-1} \text{ha}^{-1}$) is often used, instead of rainfall intensity I (Kotowski, 2011).

Intense and so maximum rainfall, with duration of up to several hours, are the most important issues in sewer systems dimensioning since they cause the highest flows in storm water conduits or in combined sewer systems.

Not all runoff within urban area – rainwater catchment with F area – flows into the sewer system. Part of precipitation wets the surface and evaporates. Another part fills terrains and soaks into the ground, or flows outside the catchment of sewer system in accordance with the land decrease. Precipitation height that is not the part of flow is defined as a loss. Intensity or height relations between rainfall and its duration and frequency are developed for many geographic regions. They are qualitatively related to each other, but they are not quantitatively identical. Basic form of quantitative description of rainfall are models describing the dependencies of rainfall intensity I (mm min^{-1}) or unit rainfall intensity q ($\text{dm}^3 \text{s}^{-1} \text{ha}^{-1}$) defined as rainfall per unit of time divided by the test area, or the height h (mm) of precipitation on its duration t and probability p_r , or alterable precipitation frequency C (years) (Błaszczak *et al.*, 1983; Kotowski, 2011). Probability p_r of rain emergence with frequency C of its occurrence defines the relation below:

$$p_r = \frac{100}{C} \quad (\%) \quad (2.1)$$

Rain probability defines how many times, over the century, occurs the rain with the intensity equal or greater than the assumed one. Frequency of rain occurrence expressed in years indicates that in given C summer cycle, a rain with intensity equal or greater than q occurs at least once. For example, if probability $p_r = 10\%$ is assumed, it means that the rain with intensity I and duration t with rain with higher intensity can occur about 10 times during the century, that is once in 10 years ($C=10$). The value of rain occurrence probability, assumed in hydraulic calculations is not hydrological important, but determines the safety of trouble-free functioning of drainage devices (Edel, 2006).

2.1.1 Precipitation model for sewer system designing

In Poland, the most common model used for sewer system designing is the Błaszczyk's model of 1954 (Błaszczyk *et al.*, 1983) presented below:

$$q = \frac{6.631 \sqrt[3]{H_n^2 C_r}}{t^{2/3}} \quad (2.2)$$

where: q – unit rainfall intensity, average in time t ($\text{dm}^3 \text{s}^{-1} \text{ha}^{-1}$), t – rain duration (min), H_n – height of normal precipitation – min. 30 annual average from several years (mm), C_r – frequency (repetition) of rain occurrence with intensity q (years).

The intensity of reliable rain for storm water system can also be determined from the formula below (Klepacka *et al.*, 1999):

$$q = \frac{A_p}{t^{0.67}} \quad (2.3)$$

where: A_p – coefficient depended on the probability of rain occurrence, and the average annual amount of precipitation ($\text{dm}^3 \text{min}^{0.67} \text{s}^{-1} \text{ha}^{-1}$), t – rain duration (min).

A_p coefficient can be calculated from the equation below (Szpindor, 1992):

$$A_p = 6.631 \sqrt[3]{H_a^2 C_r} \quad (2.4)$$

where: H_a – the average annual amount of precipitation (mm), C_r – frequency (repetition) of rain occurrence with intensity q (years).

A_p coefficient can also be read from the table below:

Table 2.1. A_p coefficient values (Edel, 2006)

Value of the probability of rain p_r (%)	A_p coefficient value in dependence with the average annual amount of precipitation H (mm)			
	up to 800	up to 1000	up to 1200	up to 1500
5	1276	1290	1300	1378
10	1013	1083	1134	1202
20	804	920	980	1025
50	592	720	750	796
100	470	572	593	627

Synthetic pluviograms belong to the group of models taking into account the variability of rainfall intensity in time. Synthetic pluviogram of the rain with a specific probability can be defined by pluviogram created with maximum intensities of the rains occurring with a specific probability in individual time periods. Each time interval may correspond to different number of rains. Each probability, however, corresponds to different synthetic pluviogram. Analysed precipitation from a long period is divided into intervals of 5 to 10 minutes. Then, rainfall intensity and tabular

list are calculated from each partial interval. Received compounds between the rainfall intensity in defined partial time interval and the probability of its occurrence, is the basis for the development of synthetic pluviograms. This kind of pluviogram demonstrates the maximum phase rainfall intensity as a function of rain duration for defined probability of occurrence and exceeded defined confidence level.

2.1.2 Rules of balancing of storm water outflow

Phenomenon of rainfall-runoff in urbanized catchment is a complex issue and difficult to generalize. The process of storm water runoff can be divided into three phases: runoff creation, runoff concentration, and sewer outflow. In calculations in sewer systems usually crucial is participation of outflow from the sealed surface areas. Runoff concentration includes converting surface divided effective precipitation into the outflow hydrograph created in the lowest point of the analysed catchment. The processes of runoff on the surface (time shift) and delay effects (field retention) play the role in it. Sewer outflow is also a subject to the effects of sifs in time and retention, as well, among others as a result of the existence of flow resistances and filling of the channels for the calculation flow (*Kotowski, 2011*).

General formula for reliable stream of storm water runoff Q from the catchment has the form:

$$Q = q_i \cdot \varphi \cdot \psi \cdot F \quad (2.5)$$

where: q_i – individual intensity of rain ($\text{dm}^3 \text{ s}^{-1} \text{ ha}^{-1}$), φ – runoff delay factor (-), ψ – runoff factor (-), F – catchment area (ha).

Delay factor also called the reduction factor of rainfall intensity is associated with runoff time of storm water from the furthest point of the catchment to the calculation section. Delay factor φ is mainly depended on the surface and shape of the catchment. It can be determined on the basis of the Bürkli-Ziegler dependence (*Suligowski, 2000*):

$$\varphi = \frac{1}{\sqrt[3]{F}} \quad (2.6)$$

where: F – catchment area (ha), n – factor depending on the decrease and shape of the catchment (-).

For intermediate conditions, in the case when terrain and channels decrease determines speed of 1.2 m s^{-1} , and the catchment length is twice more its width, factor $n=6$ can be assumed. Factor $n=4$ can be assumed in the case of catchment with low decrease and lengthen shape, however $n=8$ in catchment with compact area (*Suligowski, 2000*).

Runoff factor is defined as the ratio between the amount of water, which will flow from the analysed surface into the channel and the amount of water which fell on the surface in the form of precipitation. It is characteristic value for each kind of catchment and it can be determined as follows (*Galabuda, 2008*):

$$\psi = \frac{Q_{sp}}{Q_{op}} \leq 1 \quad (2.7)$$

where: Q_{sp} – amount of runoff from the given area ($\text{dm}^3 \text{ s}^{-1}$), Q_{op} – amount of precipitation on given area ($\text{dm}^3 \text{ s}^{-1}$).

The most important factors that determine the runoff coefficient are as follows (Edel, 2006): type of land cover, slope, surface temperature, initial state of surface moisture, geological structure of upper surfaces. Factor having the greatest impact on the runoff coefficient is a kind of surface seal. The table below depicts ψ factor values in dependence with the kind of surface.

Table 2.2. Runoff coefficient value for various kinds of surfaces (Gałabuda, 2008)

Surface	Coefficient ψ
Leak-proof roofs (sheet metal, roofing paper)	0.90–0.95
Bituminous roads	0.85–0.90
Stone and clinker paving	0.75–0.85
Paving as above but without the filled welds	0.50–0.70
Worse paving without filled welds	0.40–0.50
Broke stone roads	0.25–0.60
Gravel roads	0.15–0.30
Unpaved surfaces	0.10–0.20
Parks, gardens, meadows, lawns	0.00–0.10

If in a given area surfaces with various runoff coefficients occur, substitute coefficient for the whole catchment can be determined using weight average. In the case of cities, runoff coefficient can be assumed in dependence with the density of building. Runoff coefficient value for different types of building is given in table 2.3.

Table 2.3. Runoff coefficient value for different types of building (Edel, 2006)

Type of buildings	Coefficient ψ
Very thick buildings (old neighbourhoods) with paved courtyards	0.7–0.9
Compact buildings	0.5–0.7
Scattered buildings	0.3–0.5
Residential buildings	0.2–0.3
Inbuilt areas	0.1–0.2
Parks and green areas	0.0–0.1

2.1.3 Methods of runoffs estimation

Two methods of runoffs estimation are commonly used:

Method of constant rain intensities – this is shortened method applied in preliminary projects and helpful in calculating catchments with the area greater than 50 hectares. This method uses the relationship between the rainfall intensity and the catchment area. At the very beginning of calculations, it is necessary to assume that rain time is equal to the time the rain flows through the channel. Then set it on the basis of channel length and the average flow velocity of wastewater in the channel in order to determine the reliable rainfall intensity.

Methods of border rain intensities – this method consists in determining the reliable rain and its parameters – intensity and duration – for each point of catchment.

In this method, the maximum rainfall intensity is determined as the sum of:

- retention time of the field,
- time of wastewater outflow to the channel,
- time of wastewater outflow from the beginning of the channel to the analysed calculation point.

Sewer system in the method of border intensities is calculated only for junctions, and not in each of its point. Values calculated in junction are reliable for the entire section above the concerned junction, up to the next one (Edel, 2006).

2.2 Snowmelt

Besides the rainfall, there are also snowmelt drained to the sewer system. This kind of water before draining to the receiver must be subjected to treatment, especially if it comes from leak-proof, highly contaminated areas (for instance, city centres, industrial areas). Volume of this kind of water can be determined on the basis of the standard of snow load, atlas of snow cover.

2.3 Groundwater

Besides the rainfall and melt water, also groundwater can enter to the storm water system as well as to the combined one. Sewer channels can be located above or below the groundwater table. In the first case, the movement of groundwater takes place in the conditions of incomplete saturation of soil pores with water (aeration zone), in the second one, however, in their complete saturation (saturation zone). Groundwater goes to the sewer system mainly through its channels' leak, which is referred to as infiltration. There is also possible opposite possibility – transported wastewater through the channels' leaks can enter to the soil and groundwater. This process is defined as exfiltration.

2.4 Surface runoff modelling

There are many methods of calculation and modelling the surface of water runoff going into the sewer system. SWMM 5.0 program uses the module RUNOFF to calculate the surface runoff (hydrological model). This module uses the model of catchment, which is divided into any number of sub-catchments with known area and defined hydrological characteristic. Modelling of rainfall-runoff process is done by using a model of non-linear reservoir. In this model, catchment shape is not a crucial issue. Therefore, catchments are often presented in a symbolic way using simple plane figures. Other parameters describing catchments, such as: width of the runoff, degree of surface sealing, surface slope in the flow direction, volume of field retention, Manning coefficient of roughness, and soil characteristics in terms of infiltration rate (for sealed catchments) are very important. Each of sub-catchments ought to be attached to the appropriate junction of storm water system or to the other sub-catchment. Otherwise, the program will generate errors and the model based on it will not function appropriately. Additionally, for each catchment, part of the sealed one with potentially smooth surface, on which retention of rain-water is zero, can be declared.

As far as unsealed surfaces are concerned, program calculates, for each time-step, balance of the water from precipitation and infiltration (that is surface water penetration to the deeper layer of soil). In order to do this, it uses one of three described below methods: Horton formula, the Green-Ampt's one, or the Curve Number Method.

Horton formula assumes that effective precipitation is formed when total precipitation intensity will be greater than the maximum possible intensity of infiltration (Rossman, 2010).

This method is based on the empirical observations, which results in the fact that soil absorption decreases asymptotically from the maximum initial value to minimal final. The shape of decline curve, however, can be determined by the time constant. Water that has accumulated on the surface due to the field retention is also subject to infiltration (Zawilski and Sakson, 2008).

Input data required for the Horton method are as follows (Rossman, 2010):

- maximum and minimum infiltration rate,
- distribution coefficient describing speed of the falling of infiltration rate,
- time of transition of fully saturated soil to dry state with zero saturation.

Green-Ampt's formula – method used to determine the infiltration, with continuous presence of water on the surface.

Input parameters required for Green-Ampt's method are as follows (Rossman, 2010):

- hydraulic conductivity of soil,
- initial deficit of soil moisture,
- capillary suction.

Curve Number Method – the method assumes that the total infiltration capacity of a soil can be found from the soil tabulated Curve Number. At the rainfall event this capacity is depleted as a function of cumulative rainfall and remaining capacity. The input parameters for this method are the curve number and the time it takes a fully saturated soil to completely dry (Rossman, 2010). CNM method using the effective precipitation model SCS (Soil Conservation Service). In SCS model, total precipitation was divided into two parts: effective precipitation and losses.

Effective precipitation depends on the following factors:

- soil type and its moisture in the time before precipitation,
- average total precipitation,
- way of using the catchment area.

These factors can be described in a collective way using dimensionless parameter CN (Curve Number), which is related to the maximum potential retention of the catchment. The values of this coefficient range from 0 to 100.

3 Modelling of the wastewater flow in gravitational sewer system

3.1 Hydrodynamics

The hydrodynamics of conduits of gravitational sewer systems largely determines the amount of sediments accumulating on the bottom and the thickness of the biofilms, and also affects the rate and effectiveness of fragmentation of organic and inorganic particles. The considerations presented in this chapter are conducted in relation to water treated as the liquid dispersion phase of a multi-phase mixture such as sewage. In sanitary engineering issues related to hydrodynamics appear, among other, in relation hydraulic calculations of canals and conduits, understood as the determination of their shapes, dimensions, slopes, filling with sewage, and sewage flow velocities. In practice we encounter two basic instances of performing hydraulic calculations for sewer conduits. The first and the most frequent is designing sewer networks where calculations are made for individual sections between specific trunk sewers, basing on predetermined credible data on the flow rate and the adopted slope of the conduit and the roughness of its walls (*Błaszczyk et al., 1983*). The second case when calculations of this kind are performed relates to validation calculations and simulations of operation of a sewer system designed or built. Input available in such a case include information concerning the shape and dimensions of the conduit, and its filling, based on which the volumetric flow rate is calculated, the flow velocities in the conduit, and the stresses at the boundary between the sewage and the conduit walls.

3.1.1 Flow of free surface liquid

Describing the flow of sewage in a gravitational sewer system one can make use of the theory of the flow of a liquid with free surface in pressureless conduits. This is justified by the fact that in closed conduits, but not fully filled with sewage, the flow of sewage takes place solely due to the forces of gravity, inertia and friction. Movement of this type is caused by the slope, i.e. the longitudinal inclination of the conduit, and is referred to as gravitational flow (*Mitosek, 1997; Orzechowski et al., 2001*).

Gravitational flow can be divided into steady (uniform) flow and unsteady (non-uniform, variable) flow. Uniform flow takes place when the cross-section shape of the stream remains constant and is related to uniform motion. Non-uniform flow can be steady (stationary) or unsteady (non-stationary). Non-uniform flow can be divided into slowly varied and rapidly varied (*Mitosek, 1997; Orzechowski et al., 2001*). The rapidly varied non-uniform flow takes place in a situation when in channel cross-sections situated close to each other there are considerable diffe-

rences in depth. Such motion is usually caused by local obstructions disturbing the flow, and thus – in relation to a sewage conduit – can be considered as a result of its damage.

Slowly varied non-uniform flow of liquid in channels with free surface is characterised by domination of one component of the velocity vector, namely that which is directed along the axis of the channel – the sewage conduit. That property justifies treating that kind of flow as a unidimensional problem (Szymkiewicz, 2000; Huisman, 2001).

3.1.2 General equations of flow of incompressible fluid

In the general case, the flow of a viscous and incompressible liquid – this is how sewage can be characterised – is described by means of the Navier-Stokes equations (quantitative equations of motion) and the equations of motion continuity. The equations are derived from the law of conservation of momentum and the law of conservation of mass, and in the Cartesian system they have the following form:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = F_x - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\eta}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (3.1)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = F_y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\eta}{\rho} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (3.2)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = F_z - \frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{\eta}{\rho} \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (3.3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (3.4)$$

where: t – time (s), x, y, z – spatial coordinates (m), u, v, w – components of the vector of velocity in directions x, y, z , respectively (m s^{-1}), ρ – density of the fluid (kg m^{-3}), p – pressure (Pa), η – coefficient of dynamic (physical) viscosity (Pa s), F_x, F_y, F_z – components of the vector of mass forces in directions x, y, z (m s^{-2}).

The system of equations presented above, even though it describes every form of motion, is applicable only in the case of laminar flow, while the flow in sewer systems should in many cases be considered as turbulent, and flow of this type is characterised by random fluctuations both of the vector of velocity and of pressure. Due to the lack of knowledge concerning the fluctuations, following the Reynolds approach averaged values of velocity and pressure in time are introduced. The momentary values of those parameters can be presented as a sum of the mean value ($\bar{u}, \bar{v}, \bar{w}, \bar{p}$) and the deviation from the mean value (u', v', w', p') as follows (Sawicki, 1998; Szymkiewicz, 2000):

$$u = \bar{u} + u' \quad (3.5)$$

$$v = \bar{v} + v' \quad (3.6)$$

$$w = \bar{w} + w' \quad (3.7)$$

$$p = \bar{p} + p' \quad (3.8)$$

It is also possible to address the problem of flow in different manner than is the case with the Navier-Stokes equations, namely by using velocity and pressure values averaged in time. Due to the averaging of the terms of the velocity advection in time, in the equations there appears the so-called tensor of turbulent stress. Its elements are the averaged products of fluctuation of the individual components of the vector of velocity. The tensor of turbulent stress, being a function of flow turbulence, has an unknown value, which causes that in order to close the system of Reynolds equations it is necessary to seek additional empirical information connecting the turbulent stress with flow turbulence (Szymkiewicz, 2000; Rup, 2003). Usually, in the case of flow with free surface of liquid this is achieved by introducing so-called turbulent viscosity. It is assumed that turbulent stresses can be described with a term analogous to the diffusion term in the Navier-Stokes equations which describes stresses resulting from physical viscosity. The concept of turbulent viscosity relates to the average velocity, which for the simplest case means that its coefficient is constant and independent of the spatial coordinates. The components of the tensor of turbulent stress can be written briefly as follows:

$$\overline{\phi'_i \phi'_j} = -\frac{\eta^T}{\rho} \frac{\partial \bar{\phi}_i}{\partial x_j} \quad (3.9)$$

where: $i, j=1, 2, 3$, ϕ and $\bar{\phi}$ represent deviation of velocity vector components from their mean value (m s^{-1}).

Therefore, the system of Reynolds equations can be written as follows (Szymkiewicz, 2000):

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = F_x - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} (\eta + \eta^T) \nabla^2 u \quad (3.10)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = F_y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{1}{\rho} (\eta + \eta^T) \nabla^2 v \quad (3.11)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = F_z - \frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{1}{\rho} (\eta + \eta^T) \nabla^2 w \quad (3.12)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (3.13)$$

where: η^T – coefficient of turbulent viscosity ($\text{kg m}^{-1} \text{s}^{-1}$), ∇^2 – Laplace operator.

In the formal aspect, the systems of equations presented above is similar to the Navier-Stokes equations, but its interpretation is different as it describes the relations between the flow parameters – velocity and pressure – averaged in time.

As follows from empirical experiments, the value of the coefficient of turbulent viscosity η^T is considerably higher than that of η representing the dynamic viscosity (Orzechowski *et al.*, 2001). Coefficient η^T can assume values of the order of $1 \text{ kg m}^{-1}\text{s}^{-1}$ and is a function of the turbulence of flow, and not of the physical properties of the fluid as the coefficient of dynamic viscosity η which assumes values of the order of $10^{-3} \text{ kg m}^{-1}\text{s}^{-1}$ (Szymkiewicz, 2000). This justifies leaving out the dynamic viscosity from further considerations, and operating with the turbulent viscosity alone.

3.1.3 Equation of conservation of momentum in unidimensional motion

In gravitational sewer, unsteady slow can be considered as the propagation of so-called long waves, i.e. such whose amplitude is several-fold smaller than their length (Szymkiewicz, 2000; Huisman, 2001). In waves of this type the accelerations and velocities of particles in the vertical direction are negligibly small compared to their accelerations and velocities in the horizontal direction. Therefore, only one mass force will act in the vertical direction, i.e. the force resulting from the gravitational acceleration. Thus in a system of coordinates in which axis z is oriented vertically upwards, the unit mass force equals:

$$F_z = -g \quad (3.14)$$

and the equation from the Reynolds system is simplified to the expression:

$$-g - \frac{1}{\rho} \frac{\partial p}{\partial z} = 0 \quad (3.15)$$

After integrating the above equation along depth within the range from z_d to h_z (Fig. 3.1)

$$\int_{z_d}^{h_z} \frac{\partial p}{\partial z} dz = - \int_{z_d}^{h_z} \rho g dz \quad (3.16)$$

we obtain the relation:

$$p(h_z) - p(z_d) = -\rho g(h_z - z_d) \quad (3.17)$$

where: h_z – height of sewage surface above the reference (datum) level (m), z_d – height of the bottom above the assumed datum level (m).

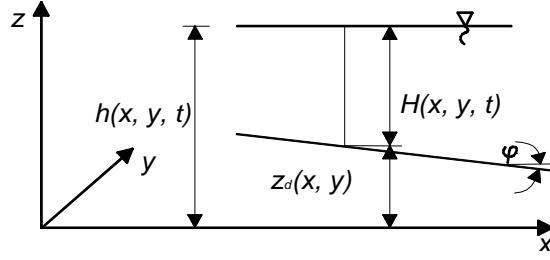


Fig. 3.1. System of coordinates in which the flow of liquid with free surface is considered (Szymkiewicz, 2000)

Since this is gravitational flow with free surface, with H describing mean cross-section depth, pressure on the surface is equal to atmospheric pressure, therefore for $z_d \leq z \leq h_z$ we can write the so-called hydrostatic law of pressure change with depth:

$$p(z) = p_a + \rho g(h_z - z) \quad (3.18)$$

where: p_a – atmospheric pressure (Pa), ρ – sewage density (kg m^{-3}), g – gravitational acceleration (m s^{-2}).

Assuming that the vectors of velocity are parallel to axis x , and their components along axis y equal 0, and thus assuming that the vector of velocity has only one component $u = u(x, z, t)$, we can write:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = F_x - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\eta^T}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (3.19)$$

Moreover, it is assumed that the bottom of the channel is inclined in the direction of axis x , and its slope is defined by angle φ (Fig. 3.1). In such a system, the only mass force acting in direction x is the component of the force of gravity oriented along the bottom of the channel:

$$F_x = -g \sin \varphi \quad (3.20)$$

A majority of sewage conduits are laid out with a small longitudinal slope of the bottom (s), so we can assume that (Mitosek, 1997; Szymkiewicz, 2000):

$$\sin \varphi \approx tg \varphi \quad (3.21)$$

Hence the force F_x can be written as follows:

$$F_x = -g \frac{\partial z_d}{\partial x} \quad (3.22)$$

This causes that equation (3.19) can be written in the following way (Szymkiewicz, 2000):

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial z_d}{\partial x} + \frac{1}{\rho} \frac{\partial}{\partial x} (p_a + \rho g H) - \frac{\eta^T}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} \right) = 0 \quad (3.23)$$

Empirical studies on flows in channels show that for the channel cross-section the vertical distribution of velocity u can be treated, with a certain approximation, as constant. Therefore the actual curvilinear distribution of velocity can be substituted with a square distribution with constant mean velocity defined as follows (Szymkiewicz, 2000; Puzyrewski and Sawicki 2000):

$$U(x, t) = \frac{1}{H} \int_{z_d}^{h_z} u(x, z, t) dz \quad (3.24)$$

where: H – the depth of the stream (m) and can be calculated as $H = h_z - z_d$.

The actual velocity of the stream, illustrated graphically in (Fig. 3.2.), can be written as the sum of the mean velocity and the deviation from the mean velocity:

$$u(z) = U + u'(z) \quad (3.25)$$

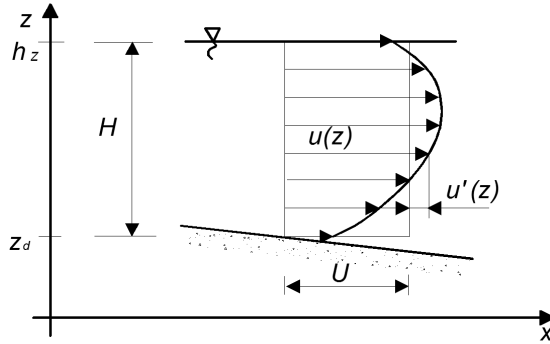


Fig. 3.2. Actual and averaged distribution of horizontal velocity vs. depth (Szymkiewicz, 2000)

As an approximation, the vertical distribution of horizontal velocity can be treated as a step function (Fig. 3.3.).

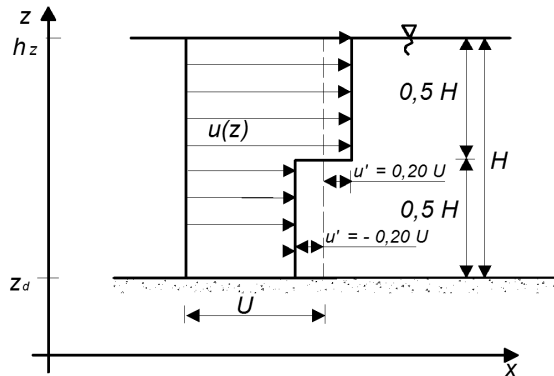


Fig. 3.3. Hypothetical vertical distribution of horizontal velocity (Szymkiewicz, 2000)

Integrating the equations of motion versus depth we eliminate variation from direction z . The end result of the integration, after dividing the result obtained by depth H which is always greater than zero, is a formula describing the flow of a liquid in a square-section channel referenced to its unit of width (Szymkiewicz, 2000):

$$\frac{\partial U}{\partial t} + \beta U \frac{\partial U}{\partial x} + g \frac{\partial}{\partial x} (H + z_d) + \frac{gn^2}{H^{4/3}} |U| U + \frac{1}{\rho} \frac{\partial p_a}{\partial x} - \frac{a}{\rho H} |W| W - \frac{\eta^D}{\rho} \frac{\partial^2 U}{\partial x^2} = 0 \quad (3.26)$$

The first two terms of the equation describe the force of inertia, the third – the force of gravity and pressure, the fourth – the force of friction against the bottom, the fifth – atmospheric pressure, the sixth – the force of friction caused by air flow, and the seventh – dispersion of momentum.

In equation (3.26), which is an equation of the conservation of momentum, there appear the following notations: β – coefficient taking into account the effect of non-uniformity of the actual distribution of velocity in an expression operating with uniform distribution on the momentum of the stream. It results from the rule of integration of derivatives with variable limits of integration. It corrects the error which appears due to the calculation of momentum on the basis of average velocity, and it is equal to or greater than one (-), η^D – coefficient of dispersive transfer of momentum in direction x (-). It permits taking into account the combined effect of turbulent viscosity η^T and that of averaging the velocity in the vertical direction, n – roughness of the channel bottom (roughness coefficient n following Manning (s m^{-1/3})). It can assume values in the range of 0.009 ÷ 0.03, where the lower value relates to smooth surfaces, e.g. coated with enamel or glazed, and the upper to damaged channels and in a state of neglect, a – an empirical coefficient accounting for air viscosity, density and profile of velocity. It is assumed that $a \approx 3.25 \cdot 10^{-3}$ kg m⁻³, W – component of the vector of air velocity acting along the x axis of the conduit (m s⁻¹), $|W|$ and $|U|$ – modules of the specified vectors.

3.1.4 Equation of conservation of mass in unidimensional motion

The equation of the conservation of mass in relation to unidimensional flow can be derived from the Reynolds system of equations. As in the case of equation of the conservation of momentum, also in this case we assume invariability of flow parameters in parallel planes x , z . The equation, reduced in this way, is integrated along depth, making use of the kinematic boundary conditions for the determination of the vertical velocities on the surface of the fluid and on the bottom. The final formula – called the equation of continuity of motion referenced to the width of the channel, can be written as follows (Szymkiewicz, 2000; Rup, 2003):

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x} (UH) = 0 \quad (3.27)$$

3.1.5 Saint-Venant equation

In many cases encountered in practice the final three terms of equation (3.26) are omitted. This is possible, as its analysis in a dimensionless system reveals a small numerical value of the term of longitudinal dispersion of momentum, compared to the other terms. In most cases, also changes in air pressure and in its flow in sewer systems are negligibly small, they may prove to be significant only in rare situations of nearly complete filling of a sewage conduit or in the case of occurrence of the so-called chimney draught. Moreover, assuming coefficient $\beta=1$ and introducing in the formula the slope of the channel s , as well as a drop in the energy line S (friction slope), we obtain a notation which, together with equation (3.27), forms the Saint-Venant systems of equations:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + g \frac{\partial H}{\partial x} = g(s - S) \quad (3.28)$$

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(UH) = 0 \quad (3.29)$$

The S parameter included in the above set of equations, describing waves propagation in open channels at their unit width, may be written as follows:

$$S = \frac{n^2}{H^{4/3}} |U| U \quad (3.30)$$

However, in engineering practice other independent variables are commonly used. The flow rate and free surface coordinates are used instead of flow velocity and sewage depth. Considering the influence of velocity distribution diversity at cross section β , and marking the cross section area as A , flow rate as Q , one must notice that considered variables refer to the whole cross section of a pipe and are properly interpreted. So, U is a mean flow velocity at given cross section and S is drop in energy line reflected to the whole cross section – connected to the hydraulic radius R_h and roughness coefficient n of the material of inner side of the pipe walls, which may be presented as (Szymkiewicz, 2000; Zoppou, 2001):

$$U(x, t) = \frac{1}{A} \iint_A u(x, y, z, t) dA = \frac{Q}{A} \quad (3.31)$$

$$S = \frac{n^2}{R_h^{4/3}} |U| U \quad (3.32)$$

where: R_h – hydraulic radius, which is a relation of cross section area A to the wetted perimeter (m), O_z – the peripheral length of contact between transported sewage and pipe material (m) (Jeżowiecka-Kabsch and Szewczyk, 2001).

Coefficient β is sometimes defined as the ratio of the square of stream momentum at the actual distribution of velocity to the square of momentum at averaged velocity in the cross-section considered:

$$\beta = \frac{\iint_A u^2 dA}{U^2 A} \quad (3.33)$$

Assuming additionally that the level of the channel bottom does not change in time, we obtain an alternative form of the system (3.28, 3.29), which is frequently employed for the description of unsteady flow in open channels (*Even et al., 2004*):

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{\beta Q^2}{A} \right) + gA \frac{\partial h}{\partial x} + g \frac{n^2}{R_h^{4/3}} \frac{|Q| Q}{A} = 0, \quad (3.34)$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (3.35)$$

where: R_h – hydraulic radius (m), A – stream cross sectional area (m²), Q – flow rate (m³ s⁻¹), β – dimensionless velocity coefficient (-), n – roughness coefficient (s m^{-1/3}).

The systems of equations presented above, (2.28, 2.29) and (2.34, 2.35), are referred to as the complete dynamic model or the dynamic wave model (*Szymkiewicz, 2000; Zoppou, 2001*). As demonstrated by numerous experiments described in the literature of the subject, it permits obtaining results with good agreement with measured data in cases when the assumptions adopted during the derivation of the equations are met, and namely:

- the motion of the fluid is a slowly varied motion,
- the force of gravity is the only mass force,
- the slope of the channel bottom is small,
- the vertical distribution of velocity is treated as uniform,
- there is no side inflow or tributary on the section of the sewage conduit under consideration,
- the fluid described is incompressible and homogeneous – with no variation of density.

The equations denoted as (3.28, 3.29) and (3.34, 3.35) are systems of first order partial differential equations, of the hyperbolic type, and describe slowly varied unsteady motion. For the solution of a system of equations of this kind it is necessary to define in prior the initial and boundary conditions, which is usually achieved by assuming that at the initial moment the flow was steady – this permits the calculation of the initial values of $z(x)$ and $Q(x)$ for time $t=t_0$ (*Mitosek, 1997*). In the case in hand the boundary conditions relate most often to the values of $z(t)$ and $Q(t)$, at the initial and final cross section of the sewage conduit, respectively.

The systems of equations discussed, in conjunction with the boundary conditions, are usually solved numerically – e.g. by means of the finite differences or finite elements methods. The full Saint-Venant equation should be used in cases when the Froude number for the system under analysis is smaller than unity ($Fr < 1$). More detailed information on the criterion Froude number is given in the next subchapter. The basic form of the Saint-Venant equation (3.28, 3.29) and some of its reduced versions require the determination of the value of drop of the energy line S which can be calculated as in formulae (3.30 and 3.32) and in the formulae presented below.

The empirical equation for the friction slope in unsteady flow can be written in the following manner proposed by French (1985) (*Huisman et al., 2000*):

$$S = \frac{1}{C_{CH}^2} \frac{1}{R_h^{2a_e}} U |U| \quad (3.36)$$

where: S – friction slope (m m^{-1}), C_{CH} – Chezy empirical roughness coefficient ($\text{m}^{1/2} \text{s}^{-1}$), a_e – empirical exponent (-).

The empirical roughness coefficient may be presented as the Darcy-Weisbach equation:

$$C_{CH} = \left(\frac{8g}{\lambda} \right)^{\frac{1}{2}} \quad (3.37)$$

Therefore it is possible to employ in the flow model the equation that is encountered in the literature under the name of the Darcy-Weisbach equation:

$$S = \frac{\lambda}{8g} \frac{1}{R_h} U |U| \quad (3.38)$$

where: U – mean axial velocity in the active cross section (m s^{-1}), λ – dimensionless coefficient of friction factor (-).

Coefficient λ is related with internal friction and with the contact surface of flow turbulence with the conduit walls, and more accurately with their roughness. The kind of material and the state of the surface of the conduit are characterised by the sand roughness index introduced by Nikuradse (1933) and studied in greater depth by Henderson (1966), who proposed the following classification of surface (*Huisman, 2001*):

$$(\text{smooth}) \quad 4 < k^* = \frac{k U_*}{\nu} < 100 \quad (\text{rough}) \quad (3.39)$$

where: k^* – dimensionless coefficient of surface roughness (-), k – coefficient of equivalent sand roughness, defined as the size of sand grains that cause the same flow resistance as that observed in experimental measurements in a given conduit (m), ν – kinematic viscosity, adopted for sewage to have the value of $1.31 \cdot 10^{-6} \text{ (m}^2 \text{s}^{-1}\text{)}$, U_* – dynamic velocity (m s^{-1}).

The coefficient of linear hydraulic resistance λ is calculated for the following cases (intervals) (*ATV-DVWK – A110P, 1988*):

- turbulent flow in hydraulic-smooth conduits – acc. to Prandtl,
- completely turbulent flow at perfect roughness – acc. to Prandtl,
- flow in conduits with natural technical roughness – acc. to Colebrook.

For calculations of sewage channels and conduits the last of the cases listed has an application, and the equation that describes it is encountered in the literature under the name of the Prandtl-Colebrook formula (*ATV-DVWK – A110P, 1988*), or the Colebrook-White equation.

The dimensionless friction factor can be calculated after the Prandtl-Colebrook formula:

$$\frac{1}{\sqrt{\lambda}} = -2 \log \left(\frac{2.51}{Re \sqrt{\lambda}} + \frac{k/D}{3.71} \right) = -2 \log \left(\frac{2.51}{Re \sqrt{\lambda}} + \frac{1}{3.71} + \frac{k}{4R_h} \right) \quad (3.40)$$

where: D – pipe diameter (m), k – wall sand roughness (m), Re – dimensionless Reynolds number (-).

$$Re = \frac{\rho U D_z}{\eta} = \frac{U 4R_h}{\nu} \quad (3.41)$$

where: ρ – density (kg m^3), η – coefficient of dynamic viscosity (Pa s), D_z – equivalent diameter of the conduit (m), $D_z = 4 R_h$ for most non-circular conduits (m).

The dimensionless coefficient of linear resistance can be described with the formula:

$$\lambda = \left[-2 \log \left(\frac{14.84 R_h}{k} \right) \right]^{-2} \quad (3.42)$$

Another method of calculation of the slope of the energy line (3.30) is the application of the Manning equation to calculate the Chezy coefficient:

$$C_{Ch} = \frac{1}{n_M} R_h^{1/6} \quad (3.43)$$

where: n_M – roughness coefficient acc. to Manning ($\text{s m}^{-1/3}$).

The approach proposed by Manning was derived for steady flow, but it is also used for unsteady flow after taking into account the relations of the energy line and n to time and to the wetted perimeter.

The Pawłowski equation is another alternative in hydrodynamic calculations, it relates the energy line slope to the roughness coefficient and to the hydraulic radius (*Walden and Stasiak, 1971; Huisman et al., 2000*):

$$S = n_M^2 \frac{1}{R_h^{2y}} U |U| \quad (3.44)$$

where: $y = 2,5\sqrt{n_M} - 0,13 + 0,75\sqrt{R_h(\sqrt{n_M} - 0,10)}$.

The equations presented above are the methods most frequently applied in practice for the description of the energy line slope.

3.1.6 Simplified equations of flow with free surface

Due to the complexity of the presented phenomenon, the Saint-Venant equation is fairly often reduced through the omission of the term accounting for the forces of inertia, and in certain cases also of the term describing the forces of pressure. The motion equation reduced in this manner, in combination with the equation of continuity, gives the model of dynamic wave and kinematic wave, respectively (Mitosek, 1997; Szymkiewicz, 2000; Zoppou, 2001).

For certain cases encountered in engineering practice a kinematic wave model can be applied where in the equation of the conservation of momentum only the forces of gravity and pressure will be included. In this description of steady flow the inclination of water surface s is parallel to the friction slope S (Walden and Stasiak, 1971; Zoppou, 2001):

$$s = S \quad (3.45)$$

In that case the flow description is often reduced to the steady flow equation (mass conservation):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (3.46)$$

$$Q = C_{CH} R_h^{1/2} s^{1/2} A \quad (3.47)$$

and

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (3.48)$$

$$A = \alpha_c Q^m \quad (3.49)$$

Equation (3.49) is a transformed Chezy equation, where the α_c coefficient and the exponent m at the value of Q can be calculated as follows:

$$\alpha_c = \frac{1}{\left(\frac{C_C s^{1/2}}{O_Z^{1/2}}\right)^{2/3}}, \quad m = \frac{2}{3} \quad (3.50)$$

Defining the Chezy coefficient by means of a relation taking into account the Manning roughness coefficient we can write:

$$\alpha_c = \frac{1}{\left(\frac{s^{1/2}}{n_M O_Z^{2/3}} \right)^{3/5}}, m = \frac{3}{5} \quad (3.51)$$

where: n_M – Manning roughness coefficient ($\text{s m}^{-1/3}$), O_Z – wetted perimeter (m), the value of m parameter depends on used equation describing α_c .

With the maximum simplification of the description of the hydrodynamics of gravitational sewer systems one can use the basic equation of continuity and the Chezy equation, in which coefficient C_{CH} , the empirical roughness coefficient is represented by the Manning equation:

$$U = M R_h^{2/3} s^{1/2} \quad (3.52)$$

$$Q = U A \quad (3.53)$$

where: U – mean flow velocity in steady conditions (m s^{-1}), R_h – hydraulic radius (m), s – slope of the channel bottom (m m^{-1}), A – conduit cross sectional flow area (m^2), M – Manning-Strickler coefficient dependent only on conduit wall roughness ($\text{m}^{1/3} \text{s}^{-1}$), values of that coefficient most frequently encountered in sewer systems are given in the Table 3.1.

Table 3.1. Coefficient n by Manning, M coefficient by Manning-Strickler (ATV-DVWK – A110P, 1988; MOUSE PIPE FLOW, 2003; Sawicki, 1998)

No	Type of surface, material	$n=M^{-1}$ ($\text{s m}^{-1/3}$)	M ($\text{m}^{1/3} \text{s}^{-1}$)
1	Smooth glaze surfaces	0.009	111
2	Planed wood	0.010	100
3	Smooth concrete	0.0118	85
4	Normal concrete	0.0133	75
5	Rough concrete	0.0147	68
6	Plastic	0.0125	80
7	Smooth stone	0.0125	80
8	Ceramics	0.0143	70
9	Iron	0.0143	70
10	Bricks	0.0167	60
11	Broken stone wall, channel in bad condition	0.020	50
12	Channel in extremely bad condition, silted	0.030	33

The presented mathematical description of water flow in open channels clearly shows that despite the flow state, hydraulic parameters such as hydraulic radius, wetted perimeter and material roughness coefficient are the most important factors in the analysis. Beside the data presented at the table 3.1, also at the SWMM 5.0

User's Manual range of Manning's coefficient for closed conduit material are presented – the Appendix A.7.

Equations describing the kinematic wave can be applied successfully when the conditions in the cross section modelled are independent of those that prevail in the space considered below. This means a situation where the Froude number $Fr > 1$.

3.1.7 Critical flow equations

An important issue from the viewpoint of sewage flow and the transport and transformation of pollutants in gravitational sewer is the type flow and the related Froude number. That number is an important component in the equation describing the reaeration of sewage during its flow in the sewage conduit. In turn, the degree of sewage reaeration determines the run of biochemical processes related with the transformation and biodegradation of the pollutants. Moreover, at Froude number values of $Fr > 1$ the simplified model of kinematic wave can be applied for the description of flows with free surface.

The energy line in a sewer conduit is raised above the sewage surface by a value equal to $\alpha u^2/(2g)$, defined as the “dynamic pressure head”. If h denotes the height of channel filling, the equation of the value of mechanical energy of the stream with relation to the channel bottom can be written as follows (Mitosek, 1997):

$$E = h + \frac{\alpha u^2}{2g} = h + \frac{\alpha Q^2}{2gA^2} \quad (3.54)$$

where: A – cross sectional area of the channel, being a function of its filling (m^2), α – Coriolis coefficient (-), related with non-uniform distribution of velocities in the cross section of the sewage stream, u – local velocity ($m\ s^{-1}$).

The value of coefficient α is always greater than unity, and increases with an increase in the diversification of velocity in the cross section. That coefficient can be defined as the quotient of the true kinetic energy of the fluid E'_k , being an integral of the kinetic energy of the stream filaments and the kinetic energy E^m_k calculated for the mean velocity (Jeżowiecka-Kabsch and Szewczyk, 2001). Sometimes coefficient α is written as (Szymkiewicz, 2000):

$$\alpha = \frac{1}{U^3} \iint_A u^3 dA \quad (3.55)$$

where: U – mean velocity in cross section ($m\ s^{-1}$), u – local velocity ($m\ s^{-1}$), A – cross sectional area (m).

Assuming a constant flow rate ($Q=\text{const}$), we accept that the energy in a given cross section varies in the function of the conduit filling, and hence we have (Mitosek, 1997; Sawicki, 1998; Orzechowski et al., 2001):

$$\begin{aligned} \text{for } h \rightarrow 0: \quad & A(h) \rightarrow 0, \quad E \rightarrow \infty, \\ \text{for } h \rightarrow \infty: \quad & A(h) \rightarrow \infty, \quad E \rightarrow \infty, \end{aligned}$$

For both of the extreme cases presented, the stream energy E increases to infinity, and therefore there must exist such a depth for which E will have a minimum value (Mitosek, 1997; Sawicki, 1998; Orzechowski et al., 2001). That depth is called the critical depth, and the motion that corresponds to it – the critical motion the criterion of which can be defined by comparing to zero the energy derivative relative to depth:

$$\frac{dE}{dh} = 1 - \frac{\alpha Q^2}{gA^3} \frac{dA}{dh} = 0 \quad (3.56)$$

The derivative of surface area relative to depth can be expressed by means of the width of the sewage table in the channel:

$$\frac{dA}{dh} = B \quad (3.57)$$

Therefore, after the transformation of the turbulent flow criterion for constant flow ($Q=\text{const}$):

$$\frac{A^3}{B} = \frac{\alpha Q^2}{g} \quad (3.58)$$

Such a criterion can also be determined by assuming a constant value of total energy $E=\text{const}$ for a variable volumetric flow Q . For such conditions the depth h will vary within the range from zero to E . Hence, for a positive value of Q there exists such a depth h at which the flow rate Q assumes the maximum value. Basing on the above we can write that:

$$1 = \frac{\alpha}{g} \left(\frac{Q}{A} \right)^2 \frac{B}{A} = \frac{\alpha u^2}{gH} \quad (3.59)$$

The Froude number resulting from the above formula (3.59) constitutes the primary criterion of similarity of phenomena with domination of the forces of gravity, and it is a measure of the ratio of the forces of inertia (component of convection) to the mass forces (gravity) (Mitosek, 1997; Orzechowski et al., 2001).

That number is often used in the modelling of phenomena related with the flow of fluids with free surface, which is the case in gravitational sewer systems. Assuming as the characteristic linear dimension of the conduit the mean hydraulic depth H and $\alpha \approx 1$, we can write that:

$$Fr = \frac{U}{\sqrt{gH}} \quad (3.60)$$

Critical motion appears in the case when the Froude number is equal to unity, which happens when (Mitosek, 1997):

- at a specific constant flow rate $Q=\text{const}$, the total stream energy head E is minimal,
- at a specific total energy head $E=\text{const}$, the flow rate Q is maximal.

All other values of critical motion are referred to as the critical parameters. Making use of the flow rate in uniform motion we can determine the channel slope s :

$$s = \frac{Q^2}{C^2 A^2 R_h} = \frac{Q^2 U}{C^2 A^3} \quad (3.61)$$

Hence, after the derivation of the criterion of critical motion we can obtain (Walden and Stasiak, 1971):

$$s_{kr} = \frac{gU}{\alpha C^2 B} \quad (3.62)$$

Basing on equation (3.60) describing the Froude number and substituting $u=u_{kr}$ for a case when $Fr=1$ we obtain:

$$u_{kr} = \sqrt{gh_{kr}} \quad (3.63)$$

The critical velocity can also be determined from the conditions of critical motion, where by including $Q=u_{kr} F$ we will obtain:

$$u_{kr} = \sqrt{\frac{g}{\alpha} \frac{A}{B}} = \sqrt{\frac{g}{\alpha} h_{kr}} \quad (3.64)$$

The critical velocity plays a role in the flow of fluids as that of the speed of sound in the flow of gases (Orzechowski *et al.*, 2001). It is equal to the speed of propagation of disturbances in unsteady flow, such as e.g. a wave on the free surface of a fluid.

The sewage conduit filling depth h_{kr} is the critical depth and it was determined for the specific shape of each conduit cross section. For the simplest case – a rectangular cross section ($A=h_{kr} B$) we have (Walden and Stasiak, 1971; Puzyrewski and Sawicki 2000):

$$h_{kr} = \sqrt[3]{\frac{\alpha Q^2}{gB^2}} \quad (3.65)$$

The above formula (3.65), substituted in equation (3.54) permits to obtain:

$$E = h_{kr} + \frac{\alpha u_{kr}^2}{2g} = h_{kr} + \frac{h_{kr}}{2} = \frac{3}{2} h_{kr} \quad (3.66)$$

and therefore:

$$h_{kr} = \frac{2}{3} E \quad (3.67)$$

Hence, we can conclude that in a rectangular section channel, for critical motion, the kinetic energy amounts to one third on the total energy of the stream.

The critical motion, being a specific case of uniform flow ($Fr=1$) does not occur spontaneously in natural conditions. It is, however, important due to the fact that it constitutes the boundary between the area of tranquil flow, known also as subcritical motion ($Fr < 1$) and the area of rapid flow – supercritical ($Fr > 1$).

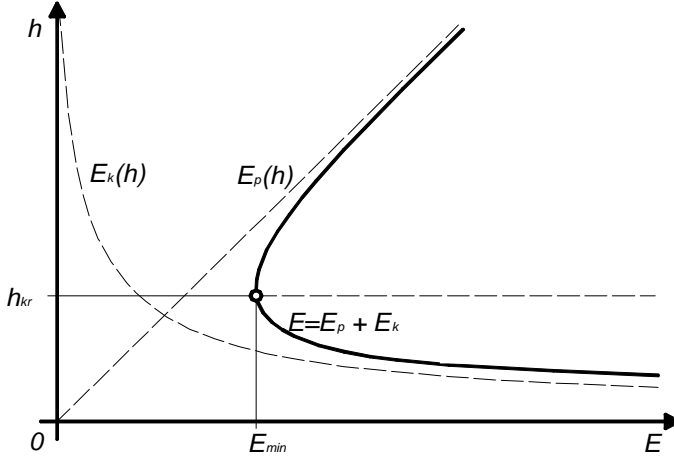


Fig. 3.4. Potential energy, kinetic energy and their sum in the function of channel filling height (Mitosek, 1997)

In the case when the channel filling height is lower than the critical ($h < h_{kr}$) the rapid flow takes place (Fig. 3.4), for which the Froude number is greater than unity. At the same time the share of kinetic energy in the total energy increases, and that of potential energy decreases.

When the flow is tranquil ($Fr < 1$), which is the case at a suitably small slope of the channel bottom, with a decrease of kinetic energy there is an increase of the potential energy of the sewage stream. Hence, the forces of gravity are the dominant forces in the system (Mitosek, 1997; Orzechowski *et al.*, 2001).

Assuming a constant flow rate ($Q=\text{const}$), we can write that:

$$E = h + \frac{\alpha u^2}{2g} = h + \frac{\alpha Q^2}{2gA^2} = E_p + E_k \quad (3.68)$$

That relation (3.68) can also be presented by means of a graph which depicts fluid flows in uniform motion at changes in kinetic and potential energy head in relation to the channel filling height (Fig. 3.4).

Analysing the graph in Fig. 3.4 one can note that in the area of rapid flow an increase in filling height there is a decrease of the total energy of the stream, while for the area of tranquil flow the total energy increases.

For the operation practice, the kind of motion in sewage conduits is of fundamental importance, if only because of the sedimentation or erosion of sediments accumulated at the bottom of channels. For a specific case the kind of motion can be determined in several ways (*Mitosek, 1997*):

- analysing the criterion equation of critical flow (3.58) – if the left-hand side is smaller than the right-hand side, the flow in the conduit is rapid. In the reverse situation we are dealing with tranquil flow,
- calculating the value of Froude number – when $Fr > 1$ the flow in the conduit is rapid,
- comparing the current flow parameters (h , s , u) with the corresponding critical parameters in the conduit under analysis.

3.2 *Advection-dispersion transport of dissolved substances*

The need to simulate the transport of polluting substances and dissolved oxygen in the sewage flux arises during development of a complete model of sewage flow in the gravitational sewer system. In properly maintained sewers, sewage flow velocity is generally uniform, which allows simplification of the model describing the pollution transport. The application of further simplifying assumptions, justified by the conditions inside the modelled object, allows to achieve credible results with acceptable efforts. This simplification can be considered taking into account the costs of data for model calibration measurement and the costs of numerical calculation.

Dissolved pollutant fractions or dissolved oxygen moving together with wastewater in the sewer can spread both horizontally and perpendicularly to the flow direction. When they disperse perpendicularly to the flow direction, the pollutant fractions will be carried to the points of the stream cross section with different mass velocities (*James, 1986*). Discharge of a sewage portion characterized by different parameters than those of the wastewater actually transported may serve as an example. The sewage velocity is generally lower at the walls and canal bottom due to friction forces that push incoming sewage towards the centre of the conduit, where the flow velocities are higher. Spread of pollutants in sewer pipes with large velocity differences in the cross section (conduits with high roughness caused by bad technical condition or sediment beds on the bottom) is increased along the flow direction, which is most important in the initial period of sewage mixing.

3.2.1 Preliminary assumptions

Most frequently, theoretical considerations of modelling are primarily focused on passive pollutants, i.e. these that have no influence on the shape of the flow velocity distribution. This exerts a crucial influence on the model description and allows separation of the water flow dynamics (regarded as a liquid dissolving phase of a multiphase mixture like sewage) from the transport of pollutants. It is assumed here that changes in the concentration of additives does not change the physical properties of the liquid phase and does not influence the dynamics of its flow (*Roman, 1986; Szymkiewicz, 2000*).

Frequently in simulation of pollutant transfer, at a certain moment the dissolved substance is locally introduced to the analysed area in the form of a concentrated stream. An example of this situation is the discharge of non-purified sewage directly to the receiver, after which pollutants are dispersed due to on-going transportation processes (*Sawicki, 2003; Łagód et al., 2009, 2010*).

The situation is slightly different in the case of the gravitational sewer system: pollutants concentrated in sewage are introduced to sewer conduits, where there is already a high level of the pollutants. In such a case, no rapid concentration changes are observed and the processes run more steadily. Then, it is often possible to distinguish two possibilities in the Cartesian coordinates system:

- the concentration of pollutants at the initial moment is constant along two spatial coordinates and changes along the third spatial variable,
- the concentration of pollutants at the initial moment is constant along the one spatial coordinate and depends on the other two.

The first situation occurs when pollutants flowing to the volume of the sewage conduit are quickly mixed in its cross section. This allows simplification of the three-dimensional spatial modelling with the one-dimensional model of pollutant concentration, which clearly and quite precisely describes the processes running in the sewer.

The second situation described can take place when mixing of incoming pollutants occurs along only one dimension of the conduit – usually the depth. It is rather infrequent situation and can develop in the case of sewage containing oil and its derivatives, which hardly mix with water and form a stable layer on the surface. In such a case, it is possible to apply the two-dimensional model instead of the three-dimensional one.

The conditions presented above allow not only formal simplification of the calculation schemes. Having practical values, they can be applied as useful models for real situations (*Sawicki, 2003; Łagód et al., 2009*). The transport of dissolved substances is traditionally described with the use of advection-dispersion formulas, which provide a one-dimensional description of sewage flow. These formulas require data supplied by hydrodynamic Saint-Venant equations.

Below, there are presented major assumptions that should be considered in the implementation of the advection-dispersion model for sewage conduits:

- pollutants are totally mixed in the cross section of the channel, which offers homogenous conditions for their transformation – decline or appearance (modelled with uniformly spatially distributed sinks or sources),
- according to Fick diffusion law, the dispersional flux is proportional to the concentration gradient.

The diameter of sewers is small in comparison to their length. Thus, vertical mixing runs relatively quickly during sewage flow, resulting in vertical homogeneity of the concentration distribution. This justifies the visible simplification of the formulas by decreasing the problem of dimensionality. Therefore, the vertical variation can be eliminated through the assumption that the mean vertical effect can be described by Fick's law and diffusion analogy.

3.2.2 Basic formulas and definitions

The measure of the quantity of a polluting substance contained in wastewater is its concentration defined as the ratio of the substance mass and the volume of the fluid, in which it is dissolved:

$$c = \frac{m}{V} \quad (3.69)$$

where: c – concentration (kg m^{-3}), m – mass of the analysed substance (kg), V – volume of the liquid (m^3).

Another value frequently used in environmental engineering for description of flow systems is the pollutant load, which defines the rate of pollutant flow in sewage per unit of time:

$$L = cQ \quad (3.70)$$

where: L – load (kg d^{-1}), Q – volumetric flow rate (stream) ($\text{m}^3 \text{s}^{-1}$).

Transport of a wastewater pollutant may be described as stream Φ defined as mass of substance passing through a unit area perpendicular to the flow direction per time unit – ($\text{kg m}^{-2} \text{s}^{-1}$). The process of transportation of any pollutant dissolved in wastewater occurs due to a combined action of basic transport mechanisms, i.e. advection and diffusion. Advection or, more specifically its spatial gradients, together with diffusion result in dispersion of pollutants.

Advection denotes transport caused by flow of the liquid, therefore, the velocity of pollution flow corresponds to that of fluid flow:

$$\Phi = U c \quad (3.71)$$

where: Φ – advective mass flow ($\text{kg m}^{-2} \text{s}^{-1}$), U – mean stream velocity (m s^{-1}).

When the stream analysed flows at constant velocity equal to the mean velocity U , advection does not introduce changes in the distribution of pollution concentration along the conduit axis. Changes will only be induced when the velocity is variable in the stream cross section. Therefore, advection contributes to spatial pollutant mass transfer. However, changes can affect the entire concentration distribution in such a way that the individual distribution variables either diverge or converge in the variable velocity field (*Sawicki, 2003*). In other words, advection can be described as influx of pollution transported with mean fluid flow velocity (*James et al., 1986*).

Diffusion is a process of transporting a pollutant to regions of its low concentrations, with diffusion flux proportional to the concentration gradient. For the direction of the x -axis, it equals (*Szymkiewicz, 2000; Merher and Stolwijk, 2009*):

$$\Phi_x = -D^M \frac{\partial c}{\partial x} \quad (3.72)$$

where: Φ_x – diffusion flux relative to the x -axis ($\text{kg m}^{-2} \text{s}^{-1}$), D^M – molecular diffusion coefficient ($\text{m}^2 \text{s}^{-1}$), $\partial c / \partial x$ – concentration gradient.

Diffusion results in equalization of the pollutant concentrations (*Sawicki, 2003*) without changing the loads.

Formula (3.72) is known as Fick's first law of diffusion, in which the minus denotes flux towards the negative gradient, i.e. in the direction of decreasing concentrations. The formula describes the so-called molecular diffusion, which exerts a significant impact on transport of dissolved substances when the dispersing phase remains at rest or when its flow is laminar. The value of the D^M coefficient (molecular diffusion) depends on the physical properties of the solvent and temperature, it is also comparable to the value of the coefficient of water dynamic viscosity ($D^M \approx 10^{-6} \text{m}^2 \text{s}^{-1}$).

Formula (3.72) is also applied for description of other processes occurring in wastewater flow, which however have not much in common with diffusion in the physical sense. Nevertheless, the effect of these processes may be comparable to the impact of the molecular diffusion mechanism. In such a case, the so-called diffusion analogy should be mentioned, for which the proportionality coefficient is interpreted in relation to the process described at a given time (*Szymkiewicz, 2000*).

3.2.3 Advection-diffusion transfer of substances

Taking into consideration a certain control value Σ limited by surface σ , it should be noted that the time-variable pollutant content might be associated with only two factors: mass flow over the limiting surface σ or transformations resulting in increased or decreased quantities of the analysed substance. This may be presented as follows (*Szymkiewicz, 2000*):

$$\frac{\partial}{\partial t} \int_{\Sigma} c d\Sigma + \int_{\sigma} q n d\sigma + \int_{\Sigma} \delta d\Sigma = 0 \quad (3.73)$$

where: q – mass flow over the limiting surface σ ($\text{kg m}^{-2} \text{s}^{-1}$), n – normal vector to surface σ , δ – internal source density specifying the intensity of decline or generation of the transported substance per wastewater volume, the so-called source element ($\text{kg m}^{-2} \text{s}^{-1}$).

Based on the Gauss-Ostrogradski theorem, the above formula can be transformed to the form:

$$\frac{\partial c}{\partial t} + \text{div } q + \delta = 0 \quad (3.74)$$

In the following equation, mass flow q is substituted by dependencies representing advective and diffusive flow, hence the formula (Szymkiewicz, 2000; Sawicki, 2003):

$$\frac{\partial c}{\partial t} + \text{div}(Uc - D^M \text{grad } c) + \delta = 0 \quad (3.75)$$

where: $U=(u, v, w)^T$ – the velocity vector, D^M – molecular diffusion tensor having non-zero elements (D_x^M, D_y^M, D_z^M) on the main diagonal only.

Using the equation of continuity for fluid with constant density, i.e. $\text{div } U=0$, and assuming that the mixture of water and substances contained therein is an isotropic medium, equation (3.75) can be expanded to (Shanahan *et al.*, 2001):

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + w \frac{\partial c}{\partial z} - \frac{\partial}{\partial x} \left(D^M \frac{\partial c}{\partial x} \right) - \frac{\partial}{\partial y} \left(D^M \frac{\partial c}{\partial y} \right) - \frac{\partial}{\partial z} \left(D^M \frac{\partial c}{\partial z} \right) + \delta = 0 \quad (3.76)$$

The above equation describes advection-diffusion in three-dimensional space taking into account the molecular diffusion process. However, sewage transport in the sewer system primarily has a character of macroscopic turbulent flow characterized by velocity and pressure fluctuations, which results in fluctuations of the pollutant concentration. Since it is not possible to obtain momentary values of these fluctuations, formula (3.76) cannot be used in practice. A solution to this problem can be the approach proposed by Reynolds for the equations of momentum conservation. By analogy, it can be assumed that momentary values of velocity and concentration are a sum of their mean temporal values and fluctuations, which, additionally transformed following the principles of operation on mean values, yields (Szymkiewicz, 2000):

$$\frac{\partial \bar{c}}{\partial t} + \text{div}(\bar{U}\bar{c} - D^M \text{grad } \bar{c} + \overline{U'c'}) + \delta = 0 \quad (3.77)$$

where: $\overline{U'c'}$ – the turbulent mass transport caused by local fluctuations of velocity and concentration.

Since there is no possibility of connecting the $\overline{U'c'}$ term with actual velocity and concentration profiles, it is represented by adequate empirical dependence. It assumes a possibility of description of turbulent transport by means of average values analogous to molecular diffusion. The turbulent diffusion coefficient (with a value reaching $10^{-3} \text{ m}^2 \text{ s}^{-1}$) is considerably higher than the molecular diffusion coefficient $D^B \gg D^M$. Therefore, molecular diffusion may be ignored in turbulent flows.

The general form of advection-dispersion equation for one dimensional transport of passive substances for the variable cross section of the canal can be described in the following way (Szymkiewicz, 2000; Zoppou, 2001):

$$\frac{\partial}{\partial t}(AC) + \frac{\partial}{\partial x}(AUC) - \frac{\partial}{\partial x}\left(AD^D \frac{\partial C}{\partial x}\right) + A\delta = 0 \quad (3.78)$$

where: $C(x,t)$ – mean cross section pollution concentration (kg m^{-3}), $U(x,t)$ – mean cross section flow velocity (m s^{-1}), A – surface of the active cross section (m^2), D^D – coefficient of longitudinal mass dispersion ($\text{m}^2 \text{ s}^{-1}$), δ – source part determining the intensity of pollution generation or decline in sewage ($\text{kg m}^{-2} \text{ s}^{-1}$).

On the assumption that there are no side inflows, it is possible to write:

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} - \frac{1}{A} \frac{\partial}{\partial x}\left(D^D A \frac{\partial C}{\partial x}\right) + \delta = 0 \quad (3.79)$$

Another simplification, after assuming a constant dispersion coefficient D^D , leads to the following form:

$$\frac{\partial C}{\partial t} + \left(U - \frac{D^D}{A} \frac{\partial A}{\partial x}\right) \frac{\partial C}{\partial x} - D^D \frac{\partial^2 C}{\partial x^2} + \delta = 0 \quad (3.80)$$

The quantitative estimation of dispersion influencing the pollutant fractions introduced to the sewer requires assessment of the intensity of turbulent diffusion and the dispersing phase mass velocity. It is possible to measure the mass velocity with the direct methods, whereas turbulent diffusion is a complicated process for quantitative determination (Huisman et al., 2000; Kashefipour and Falconer, 2002; Krukowski, 2002).

4 Brief introduction to the computer modelling of sewer systems

4.1 *Concept of model and modelling*

Technical reference books often provide concept and definition of the model as a system, which task is to imitate the distinguished features of another system, known as the original. Encyclopaedic meaning for “model” presents a physical system (physical model) or a mathematical description (mathematical model) with some properties similar to some distinguished features of the modelled object (*Wosiewicz, 1996*). Modelling is a method of testing variety of phenomena and processes or solving mathematical problems on the basis of appropriately formulated models.

4.1.1 Model description and division

According to the above defined conception of model, models can be divided into:

- physical, which reflect physical properties of real objects, they are usually built in the scale appropriate to testing, in physical models it is not easy to reflect relation between individual elements forming the system,
- mathematical, which reflect system using objects and relations being in force between them, described via mathematical relations (*Krupa, 2008*).

Mathematical model is thus treated as a mathematical description of modelled object behaviour, usually in the form of differential equations. Mathematical modelling, however, is regarded as a method of problems solving. It consists in preparation of phenomenon mathematical description and solving the obtained system of equations results. It should be emphasized that the specified models usually present reflection of the actual events, which is often significantly simplified. The effectiveness of using mathematical models of phenomena or physical processes depends directly on the level of simplification assumed in modelling. This means that in order to obtain model providing statistically significant results, thorough understanding of the phenomenon or physical process being modelled is necessary, as well as simplifications assumed in the following steps of model constructing and the available mathematical equations describing the studied phenomenon. Then, it is crucial to define a set of input data allowing the adoption of adequate initial and boundary conditions, in dependence with its degree of complexity.

In general, mathematical models provide conceptual descriptions or approximations describing systems or physical processes using mathematical equations. Modelling can range various types of systems such as biological or physical – including electrical, mechanical, hydraulic, thermodynamic, etc. Technical literature provides many definitions of the virtual model, in which, each time its different

aspects are emphasized. To highlight one of them, given term with the following adjectives is used: mathematical, numerical (digital, discrete) or computer.

Numerical or computer model of the sanitary network is a concept that has to be understood as “structure” consisted of three following elements:

- set of specific data representing the physical mappings of the network,
- mathematical equations describing hydraulic relations in the network,
- procedures and algorithms for effective solving of these equations.

In definition of the model, mathematical relations allowing for network and its hydraulic behaviour modelling, are essential (*Kwietniewski et al., 2005*).

To present the concept of mathematical model more precisely, it can be said that it is the representation of a specific real segment created for a precise purpose with usage of a finite set of symbols and mathematical operators. Whereby, this representation is lacking details and features irrelevant to the achievement of target set to the model (*Rutkowski, 2005*).

Network model is often understood in a simplified way, only as the data describing structure of the network. Thus, the model is a set of appropriate input data saved in a format understood for the program, and which forms base for the numerical calculations. However, mathematical equations describing hydraulic phenomena are attributed to the simulation program. Model for the simulation of network functioning is a program based on mathematical model describing the given network operation in the selected conditions. Depending on the type, these programs differ in speed of functioning, mathematical procedures of calculations, the scope of performed analysis and obtained information, and handling complexity, as well (*Kwietniewski et al., 2005*).

Taking the above into consideration, it can be concluded that the mathematical models of wastewater flow and transport of pollutants in sewer systems, as based on number of assumptions and requiring a large number of input data, determining of which may be burdened with errors, ought to be regarded as approximate description of physical and biochemical phenomena and not their accurate reflection. The years of experience of researchers show, however, that despite mentioned simplifications and possible inaccuracies, with the awareness of their occurrence, such models can be considered useful in scientific researches, designing and operational work.

4.1.2 Modelling description and division

Concerning the engineering systems one can say that modelling is a form of idealization of real operation performance and plays significant role in model research in which exploitative reality is a modelled object with reference to the research model having optimal parameters and the achievement of maximum effect guaranteed (*Denczew, 2006*).

General modelling is based on three principles:

- isomorphism – allows to study interconnected system components, processes or phenomena,
- analogy – allows, on the basis of decomposition of systems into subsystems, to look for the analogy among them and problems solved earlier, or analogy to other problems,
- similarities – with reference to exploitation systems similarity to operational reality.

Computer modelling is a part of support of systems operation and management in water and sewer system companies, and it concerns, among others, the hydraulic modelling (*Denczew, 2006*). Hydraulic modelling based on numerical map allows to identify the parameters of transported medium, and as a result, to assess to what extent and in which parts the system performs its function (*Rudziejewicz, 2006*).

However, mathematical modelling is the development of such mathematical model (represented e.g. by differential equation system), so that the obtained computational results express the best course of (output) modelled process represented by series of actual processes measurements. There is, therefore, a direct comparison of developed theory (as a model) with the real process data (*Rutkowski, 2005*).

4.2 Computer modelling of sewer system

Computer modelling is a very wide issue and requires combination of theoretical and practical knowledge of many fields. The crucial thing is knowledge of material aging, of which pipes are made, besides, ability to conduct field research on the network, and also proper interpretation of results, as well as knowledge of pipes hydraulics, network functioning and its cooperation with other elements of sewer system (*Kwietniewski, 2008, Leśniewski, 2008*).

Computer modelling of the network is the process of constructing the network model consisting of three main stages:

- preparation of network structure and data describing it in a graphic and descriptive way, e.g., wastewater inflows determination,
- creation of a computer file containing data about the model in a format understood for simulation program,
- verification and calibration of the model.

4.2.1 Calibration and verification of the model

Calibration and verification are undoubtedly the most important and at the same time the most difficult stages in the process of model creation. They require a lot of experience. Calibration process is defined as determining such numerical values of the input data – model parameters, to get the agreement between values

observed on real object and results of calculations obtained via model at the assumed level of accuracy. The aim of calibration is to minimize the differences between the results of measurements and calculations taking into account measurement errors (*Siwoń, 2005*).

Model calibration is usually realized in the following four stages:

- preliminary approximations of tar parameters allowing to initiate the calibration process,
- conducting the field measurements and determination of data set controlling the calibration process,
- model calibration in established state conditions with regard to a number of independent and well-defined operational and technical situations, which occurred during the field measurements, including extreme situation,
- calibration is realized on the basis of the analysis of system functioning for a longer period of time.

Calibration is usually performed by checking and possible adjustment of model parameters, such as pipes roughness, local resistances, spatial distribution and the size of wastewater inflow. Calibration process requires identification and verification of the following elements (*Kwietniewski, 2008*):

- required model accuracy,
- necessary measurement data,
- number of measurement points,
- frequency of measurements,
- network topography,
- pipes roughness coefficients,
- junction tributaries,
- pump characteristics.

Due to large number of unknowns, absolutely accurate calibration is not possible. In practice, there is always needed a compromise between the desired level of accuracy and reliability of the estimated parameters, and minimising costs of research (*Siwoń, 2005*).

According to Polish language dictionary (<http://sjp.pwn.pl>) verification is a review, methodology, procedure for resolving whether the sentence (statement, hypothesis) is true (positive verification) or false (negative verification).

It is the first step in calibration (e.g. comparing measured fillings of the conduits with the expected based on the model). It no longer includes the adjustment of calculated data to the results of measurement. Verification of the model can refer to input or output data. Verification of the input data generally involves checking if they are within the appropriate range. It may concern, e.g. diameter, roughness, or the ordinates. This procedure reduces probability of committing errors in the first

phase of model building. The output data verification is their comparison with data obtained from measurements. Calculation results are observed to see how they differ from the measurements ones. On that basis it is concluded that the model is reliable (Bylka, 2013; <http://sjp.pwn.pl/>).

Results of verification and the fact whether the model is accepted or rejected, largely depends on the assumed criteria of verification and compliance measure. In order to fully validate the model, verification should be carried out twice. The first verification is carried out on the so-called dependent material, that is, on measurement data used in model identification. The second verification is carried out on the independent measurement data, and therefore not used in model development (Soczyńska, 1997).

4.2.2 Computer simulation with calibrated model of sewer systems

Network functioning simulation is a computational process performed in simulation program on the basis of real network model and a set of selected parameters such e.g. wastewater discharge stream. The result of this process is a list of information about the work represented by the model under conditions specified by input parameters. The effects of sewer system working can be as follows: fillings, velocities and flow rates (Kwietniewski *et al.*, 2005).

Computer simulation is based on models experiments, and is used mainly in the field of sewer systems computer simulations. It has cognitive nature (accurate cognition of the network in different variants), and practical one (planning renovations and modernizations). Computer simulation is a special case of computer modelling, and is now more widely used in cognitive and decisive activities of water engineering and sewer system companies (Denczew, 2006, Licznar 2008).

Simulation can be defined as experimenting on a model of given system using the interactions and observations having equivalents in real system. The use of simulation model makes it possible to directly influence the system by values, the influencing effects of which, one would observe. Moreover, it gives possibility to observe its distinctive values on the system model (Rutkowski, 2005).

Capabilities of network simulation models (Kwietniewski *et al.*, 2005):

- knowledge about the parameters of network functioning in a variable static and dynamic conditions – analysis, evaluation and monitoring of real parameters of working network,
- identification and analysis of network failures,
- planning of existing network modernization – including the assessment of the impact of new elements on network functioning,
- evaluation of exploiting efficiency – effects of repairs and renovations,
- planning and verification of network monitoring system,
- current analysis of network functioning.

5 Introduction to SWMM 5.0 software

5.1 *Characteristics of SWMM 5.0 software*

A computer program SWMM 5.0 (Storm Water Management Model) was created by the Water Supply and Water Resources Division of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory as a result of work and research carried out in order to assess and reduce risks for human health and environment. The research program of this project was mainly based on activities involving the control of water, land, subsurface sources and air pollution. SWMM 5.0 numerical model has become a useful tool in the implementation of the tasks connected with Agency activities, due to its ability to describe/reflect a single event, or dynamic simulation of long-term qualitative and quantitative parameters of outflows from urban agglomeration. Surface runoff module in SWMM 5.0 is applied in set of subcatchments, within which precipitations occur, and water and contaminants outflow emerges (Rossman, 2010). SWMM 5.0 sewer system module reflects transport via the system of pipelines, conduits, containers, pumps and regulators. The program keeps track of the qualitative and quantitative parameters of outflow of the individual subcatchments, calculating the flow rate, level and wastewater qualitative parameters in each part of the system during the simulation consisted of multi-time steps. It is possible with the application to analyse in detail sanitary sewer, storm water runoff and the combined one, for both branched as well as ring system, in each stage of construction.

5.2 *Brief history and capability description of SWMM*

SWMM program in its first version was developed by USEPA in 1971. For many years it was used mostly for scientific purposes due to the difficult service – troublesome procedure for data preparation, and lack of data visualization connected with network structure and results of calculations. In 1994 the version working on MS Windows OS was prepared, but from the perspective of these days, it was very functionally limited and guaranteed only calculations of the systems built mainly of 200 objects. Since the nineties of XX-th, century SWMM has been used to prepare the several commercial simulation software packages. MIKE and SWMM by DHI of Denmark, and Hystem-Extran created by ITWH in Hanover, are among the most famous programs. In these applications, algorithms were used to solve the differential equation of unsteady flow, modelled on those implemented with SWMM, which are then supplemented with graphic visualization and developed database.

Software in its basic form, is free accessible on the website. Together with the program, it is possible to download the user manual (in English) including files containing source codes allowing for adapting it to user's personal requirements, for in-

stance, to create the other language versions. The current version of the package, besides the computational block includes an integrated database and graphic module. Software allows to calculate the surface runoff and flow in channels, and also modelling of quality change of wastewater and the sedimentation process (*Skotnicki, 2005*).

The database collects information about the modelled structure of sewer system (parameters of catchments, junctions and collectors), and data concerning connections between these objects. Data relating to the network and calculation results are stored in separate files. Calculation module collects the modelled system parameters from the database together with additional relevant information, for instance, precipitation characteristics, and performs hydraulic and hydrological calculations passing the results back to the database. Calculations are performed in three stages. The first is the appointment of so-called “effective precipitation”, that is the volume of precipitation involved in outflow formation. The effective precipitation is total precipitation decreased of hydrological losses resulting from evaporation, wetting of catchment surface, surface retention, and infiltration. Then, the effective precipitation is converted in the catchment runoff. It is the hydrological part of calculations often called precipitation-outflow transformation. In the third, hydraulic part of calculations, network channels runoff is determined. It is evoked by the storm water outflow from the catchment calculated in the previous stage. It is possible to calculate the flow in collector with free surface and under the pressure. This program also allows to simulate the phenomenon of wastewater impact on the ground (*Skotnicki, 2005*).

Although this program was developed to simulate the processes occurring in the storm water system and the combined ones, similar processes for sanitary sewer systems can be also simulated. In this case, hydrological stages of calculations connected with the formation of surface runoff would be omitted. They are often called precipitation-outflow transformation (catchment surface, surface retention, infiltration, evaporation, effective precipitation, catchment outflow, etc.).

Hydraulic stage of calculations sets flow in channels caused by wastewater introduced to the network by its users, or by storm water runoff calculated in the previous stage. Program allows to calculate the flow in pressure pipe, and with free wastewater surface. Simulation of overflowing, that is the phenomenon of wastewater flow on the ground, is also possible. Additional features of the program include tools allowing for changing the wastewater quality while flowing through channels, or the calculation of snowmelt – surface runoff produced from melting snow.

With SWMM 5.0 program the following issues can be solved (*Rossman, 2010*):

- calculation of the flow rate of sanitary sewers and storm water runoffs,
- calculation of the flow intensity in different types of sewer systems,
- determination of filling the gully with wastewater,
- determination of the wastewater volume spilled outside from the sewer system,

- determination of the storm water infiltrating into unsaturated soil layers,
- estimation of evaporation on the stagnant water surfaces,
- calculation of the surface runoff,
- opportunity to include in the calculation of sewer system functioning the following objects: pumps, overflows, outlets, consumption regulator, distribution chambers, and reservoirs,
- estimation of contamination runoff from the catchment surface during down-pour.

5.3 Calculation of surface runoff by SWMM 5.0

Surface runoff in SWMM 5.0 is described by the inflow and outflow from so-called subcatchment areas. Inflow to the subcatchment areas can come from rainfall, snow melting or runoffs from other subcatchments. The difference between the inflow to subcatchment and sewer system is defined as losses. These include infiltration, evaporation, and surface runoff. According to program assumptions, runoff from subcatchment area occurs when the water depth exceeds the maximum possible retention. Water depth on the subcatchment surface is calculated with the equation of water balance. Surface runoff in SWMM 5.0 is calculated from the Manning's equation (Rossman, 2010).

$$Q_s = W_c \cdot \frac{1.49}{n_c} (d + d_p)^{5/2} \cdot S_s^{1/2} \quad (5.1)$$

where: Q_s – surface runoff ($\text{m}^3 \text{s}^{-1}$), W_c – catchment width (m), n_c – Manning's roughness of catchment (-), d_p – maximum depression storage (m), d – depth of water over the subcatchment (m), S_s – subcatchment slope (m m^{-1}).

Figure 5.1 shows a schematic transformation of rain, snow and inflow from the other subcatchment surface into surface runoff, used symbol was described by the equation 5.1.

Surface runoff, calculated from the Manning's equation, enters the sewer system through the inflow into junction defined by the user, or it can flow freely to the surface of another indicated subcatchment.

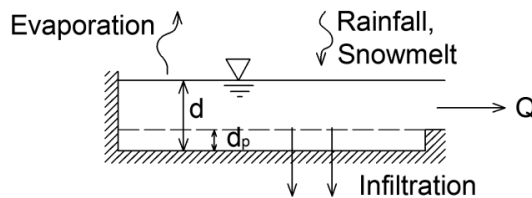


Fig. 5.1. Conceptual view of surface runoff in SWMM 5.0 (Rossman, 2010)

5.3.1 Methods of calculating the infiltration in SWMM 5.0

Infiltration is the process of runoff entering from the ground surface into unsaturated soil layers – permeable subcatchment areas. SWMM 5.0 offers three ways to calculate infiltration:

Horton equation – assumes that effective precipitation $OE(t)$, identified with surface power, arises when intensity of total precipitation $OC(t)$ exceeds maximum possible intensity of infiltration $INF(t)$.

$$OE(t) = \begin{cases} OC(t) - INF(t) & \text{when } OC(t) \geq INF(t) \\ 0 & \text{when } OC(t) < INF(t) \end{cases} \quad (5.2)$$

The curve of maximum capacity of infiltration $INF(t)$ when $OC(t) \geq INF(t)$, depends only on the initial soil moisture in aeration zone.

The Horton's concept leads to the conclusion that effective precipitation depends on two factors variable in time:

- initial soil moisture (at the start of precipitation, that is $t=0$),
- intensity of total precipitation $OC(t)$ and relatively stable characteristics of soil and vegetation cover.

This method is based on empirical observations showing that infiltration decreases exponentially from the initial maximum to minimum level during prolonged precipitation. Required input parameters for this method, in SWMM 5.0, are maximum and minimum level of infiltration, distribution coefficient describing how quickly infiltration level decreases in time, and required time of transition of completely saturated soil to the level with zero saturation (Rossman, 2010). These parameters are available in help menu of SWMM 5.0 as "Horton infiltration parameters".

SWMM 5.0 uses the Horton's equation to calculate infiltration as a function of time (Rossman, 2010):

$$f_p = f_\infty + (f_0 - f_\infty) \cdot e^{-a_i t} \quad (5.3)$$

where: f_p – amount of water infiltrating into the ground (m s^{-1}), f_∞ – maximum or minimum f_p value in time equal infinity (m s^{-1}), f_0 – maximum or initial infiltration (m s^{-1}), t – time since the beginning of precipitation (s), a_i – constant of infiltration intensity (s^{-1}).

There are research results indicating inadequacy of the Horton's model in the Polish conditions for a big catchments. The study of surface infiltration carried out in the catchment of the Skawa River revealed the average intensity of infiltration from a dozen to several thousand (mm h^{-1}), in dependence with type of soil and vegetal cover. These values practically exclude the possibility of effective precipitation description within the Horton's formula (Żelaziński, 2013).

Green-Ampt's Equation – this method was developed to determine the infiltration in the case when water is still present on the surface. Mein and Larson revealed how this equation can be adapted to uniform rain, and suggested how the parameter

of capillary suction can be defined (Rossman, 2010). The Mein-Larson's model is two-phase model. The first stage predicts the volume of water which will be infiltrated before the catchment surface will be saturated. Since the saturation, the volume of infiltrated water is calculated from the Green-Ampt's.

$$\text{For } F_i < F_s \quad F_s = \frac{S_c \cdot \text{IMD}}{\frac{i}{K_s} - 1} \quad \text{for } i > K_s \quad (5.4)$$

$$\text{for } F_i \geq F_s \quad f_p = K_s \left(1 + \frac{S_c \cdot \text{IMD}}{F_i} \right) \quad (5.5)$$

where: f_p – amount of infiltrated water (m s^{-1}), i – precipitation intensity (m s^{-1}), F_i – total value of infiltration at a given time (m), F_s – total value of infiltration needed to saturate the catchment (m), S_c – average capillary suction from the soaked ground ($\text{m H}_2\text{O}$), IMD – initial moisture deficit (m m^{-1}), K_s – saturated hydraulic conductivity of soil (m s^{-1}) (Rossman, 2010).

Equation 5.4 revealed that the amount of water required for saturation is depended on instantaneous intensity of rain. If the total value of infiltration at a given time is greater than the total value of infiltration required to saturate the catchment, calculations are carried out using equation 5.5. When precipitation is lower than the value of saturated hydraulic conductivity of soil, all rain infiltrates and is used to calculate and correct the initial lack of moisture IMD (Rossman, 2010).

After choosing Green-Ampt's method of infiltration calculation, SWMM 5.0 requires the following parameters: initial moisture deficit of the soil, the soil's hydraulic conductivity, suction head at the wetting front (Rossman, 2010). These parameters are available in help menu of SWMM 5.0 in the "Green-Ampt infiltration parameters".

Curve number method – this method uses a model of Soil Conservation Service – SCS. In the SCS model the total precipitation was divided into the effective one and losses. Effective precipitation is defined as a part of total precipitation that through runoff forms hydrograph of surface outflow. Effective precipitation is therefore dependent upon the average total precipitation, and soil type, use of catchment area, and soil moisture preceding the rainfall. All of these factors are included in the dimensionless parameter CN (Curve Number) associated with maximum potential retention of catchment with values varying from 0 to 100 (www.dziobak.pl).

Input parameters for this method required by SWMM 5.0 are as follows: data about the ground parameters, soil hydraulic conductivity and required time of completely saturated soil transition to a level where saturation is zero (Rossman, 2010). Required parameters can be found in the publication SCS Urban Hydrology for Small Watersheds, 2nd Ed., (TR-55), June 1986, or in help menu of SWMM 5.0 by selecting "Curve Number Infiltration Parameters".

5.3.2 Groundwater flow calculation in SWMM 5.0

SWMM 5.0 in calculation uses two-zone model of groundwater showed in Figure 5.2. The upper zone is unsaturated with different moisture content, while the bottom zone is fully saturated. The moisture content in it is constant.

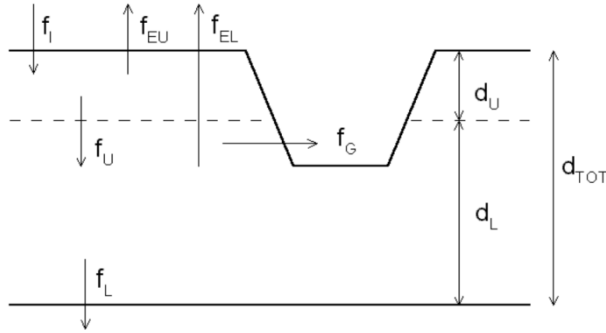


Fig. 5.2. Two-zone model of groundwater (Rossman, 2010)

In figure 5.2 the following parameters were mentioned: f_i – infiltration from the surface, f_{EU} – evapotranspiration from the upper zone, f_U – percolation from the upper to the lower zone that depends on the moisture content in the upper zone, and the d_U height, f_{EL} – evapotranspiration from the bottom zone that is a function of the upper zone d_U , f_L – percolation from the bottom zone to the groundwater located lower – it is dependent on the height of the bottom zone d_L , f_G – lateral inflow of groundwater to the sewer system depends on the height of the bottom zone d_L and the depth of junction or conduit arrangement that receive a supply, d_U – height of the upper unsaturated zone, d_L – height of the bottom saturated zone, d_{TOT} – total height of saturated and unsaturated zone (Rossman, 2010).

After calculating flows occurring during a specified time step, water balance equation is written out, as well as calculation of a new level of groundwater and unsaturated zone. Groundwater flow is calculated from equation 3.7 placed in chapter 3.4.4.

5.3.3 Snow melting consideration by SWMM 5.0 in estimating runoff quantity

Snow melting calculation in SWMM 5.0 is part of surface runoff modelling. Level of snow in a given subcatchment is estimated by applying snow accumulation, changes in positioning due to removing, and of course, by taking into account snow melting. Snow after melt is treated as an additional runoff for given subcatchment, on which it was located (Rossman, 2010).

5.3.4 Surface retention used by SWMM 5.0 to calculate flows

In a situation when the maximum level of transported wastewater in the junction is exceeded, its flow over the surface occurs. SWMM 5.0 is equipped with function that allows for temporal retention of wastewater inflow that emerged from sewer system during its overload, and to re-introduce it into the drain, when wastewater level in conduits is stabilized. For the steady flow and kinematic wave methods, wastewater that emerged from the sewer system outside, in further calculations is treated as excess, which is retentioned temporarily. Then, when wastewater level in sewer system is stable, excess is entered into the system. For the dynamic wave method, in determining surface retention, for junction, the area where wastewater may be temporarily stored is required to be introduced. This area is located above a given junction. If the flow that emerged from the system is not able to retention in a given area, it gravitationally flows down, for instance, roads, streets, avenues, to open conduits or drains (*Rossman, 2010*).

5.3.5 Methods used by SWMM 5.0 to determine wastewater quality

SWMM 5.0 bases calculations of the quality of wastewater in conduits on the fact that conduit acts as continuous tank reactor with ideal mixing (CSTR – Continuously Stirred Tank Reactor). Flow quality calculations will be the most accurate if time of wastewater flow through a conduit will be equal to time step assigned to the analysis. Concentration of contaminants present in the conduit is determined by using mass conservation law taking into consideration the average flow rate or conduits filling. Wastewater quality in the tanks is calculated in the same way as for the pipes. For the other junction points (e.g. drains), which do not need volume indication, wastewater quality flowing from the junction is calculated by mixing concentration of contaminants flowing into the junction (*Rossman, 2010*).

5.4 Getting started with SWMM 5.0

SWMM 5.0 can be used on PCs operating in the WINDOWS98/NT/Me/2000/XP/Vista/7. The software is available as a single file which contains a self-extracting setup. When setup is run, program starts to install automatically. During the installation, the user will be asked about location where the file should be unpacked and installed. If there is a need to remove program from the computer, it can be done by deleting directory where it is installed. This is sufficient because SWMM 5.0 does not save any information to the registry of system during the installation (*Rossman, 2010*).

5.4.1 Main dialogue

Main dialogue of SWMM 5.0 is divided into seven parts as it can be seen in Figure 5.3. They are: Main Menu, several Toolbars, a Status Bar, the Study Area Map window, a Browser panel, and a Property Editor window (*Rossman, 2010*).

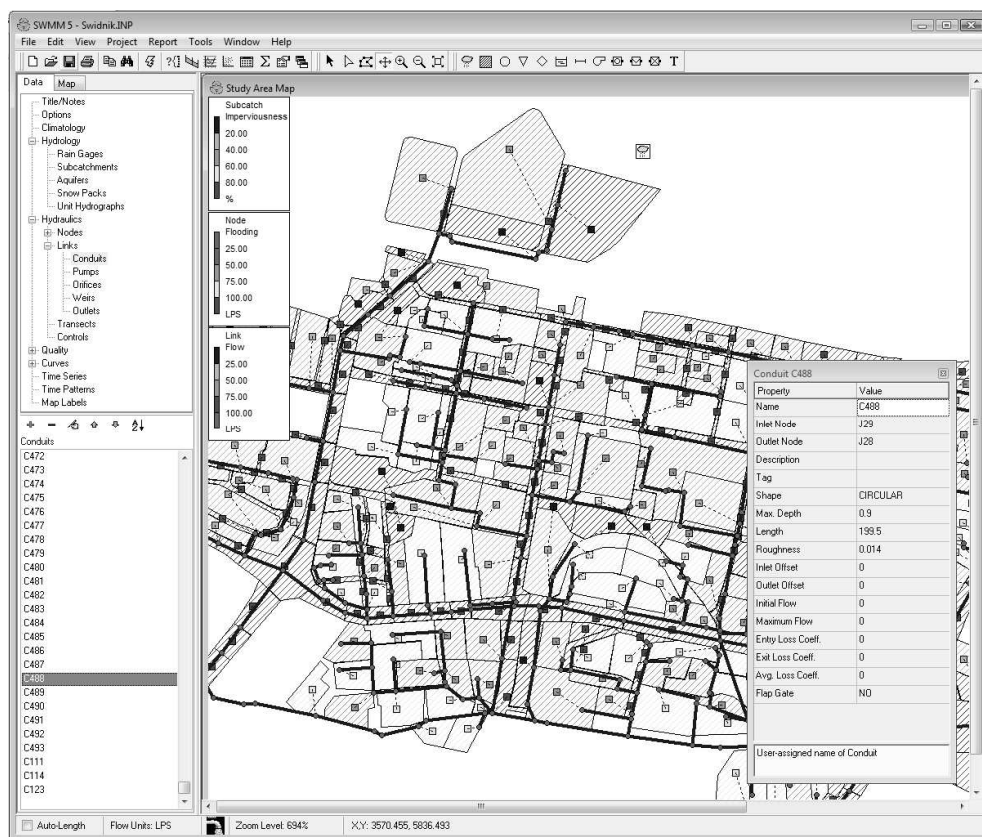


Fig. 5.3. Basic element of SWMM 5.0

SWMM 5.0 Main Menu, like in the other software running in the Windows environment, is located at the top of dialogue. It consists functions to control the program such as: File, Edit, View, Project, Report, Tools, Window, and Help. With these functions various operations can be performed, for instance, opening previously saved data, saving data, loading background, choosing default properties for newly created project. More detailed description of the selected functions of Main Menu will be presented later in this work. Toolbars in the program are divided into four basic categories: standard, maps, drawing objects, and animation. They can be freely hide or activate by choosing in Main Menu *View* → *Toolbars*, and then checking or unchecking the appropriate toolbar category.

Map is a space where network layout is created, and it is used to visualise drawn objects, and to present the results of calculations.

Browser panel is divided into two tabs: *Data*, and *Map*.

Selecting *Data* provides access to all data in the project. Below the browser window, there are icons for adding, deleting or editing objects selected in a browser. Panel containing these icons is showed in Figure 5.4.



Fig. 5.4. Graphic browser panel

Selecting *Map* in *Browser panel* allows to choose junction points for sub-catchment, and connections of certain parameters such as: connections length, wastewater flow rate, subcatchment area, ordinate for junction point. Selected parameters are showed as a legend in map window (Fig. 5.3). Property editor is used to change objects' properties contained in the project. It appears when given object in the map window is selected by double clicking, or marking it and choosing *Edit Object* from the browser panel showed in Fig. 5.4.

Another, the third method of editing is identifying the object occurring in the map window, and then right-click and select *Properties*. In order to cancel the value entered into *Property Editor*, Esc should be selected before closing a window of a given editor.

Status Bar is located in the bottom part of dialogue. From the left, there are showed the following issues: state of automatic calculation of conduit length (included or excluded), current unit of flow volume (given in Table 5.1), flow status, level of map zoom, and coordinates of cursor position (X and Y). Flow status is showed graphically as a tap, which may be represented as follows:



with no flowing water, when calculations have not been carried out yet,




with flowing water, when calculations have been carried out properly,



cracked tap with flowing water, when in previously properly carried calculations any data was edited.

5.4.2 Creating a new project

In order to create new project, click on the icon  on the Standard toolbar, or select *Main Menu* → *File* → *New*. At the first time, an essential element before creating a network is to check and possibly modify default settings. This is done by selecting *Main Menu* → *Project* → *Defaults* – which is showed in Fig. 5.5.

Adjusting default settings is a great facility while creating network composed of multiple elements with similar properties. Once assigned attributes in default settings are automatically assigned to all newly introduced objects. Defining default properties should be performed before drawing the network.

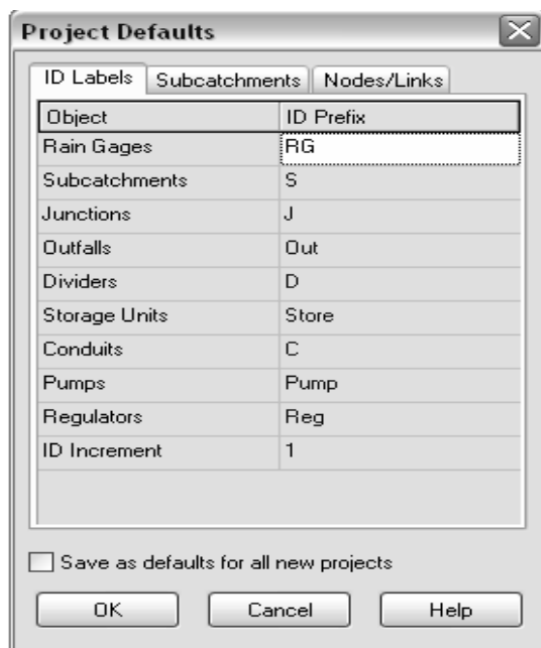


Fig. 5.5. Default settings, tab of objects identifiers

Figure 5.5 depicts the three tabs. For each of them it is possible to save the default settings for all newly created projects. In order to do this, select window showed in Fig 5.5 “Save as defaults for all new projects”. In the first tab ID Labels, in ID Prefix identifier symbol for each object can be entered. Special attention deserves the last point, that is, ID Increment set default as 1.

It is value, of which the numeric identifier will be increased in particular objects. In this case, elements consisting network will be described in ascending order, every 1. For instance, if junctions are being marked as “J”, enter a prefix letter “J”. As a result (at increment of 1) other junctions will be marked: J1, J2, J3, and so on (Rossman, 2010).

When ID Prefix is left blank for individual objects, then these objects will be mark only by numbers.

More detailed description of the characteristics of individual objects is showed in Chapter 5.4.4. Description of the subcatchment characteristics is in chapter 5.4.4., however the detailed description of methods of infiltration calculation is in chapter 5.3.1. More detailed description of junctions and connections characteristics is in chapter 5.4.4, however description of methods of flow calculation is in chapter 5.4.6. In SWMM 5.0 connections are identified both with open conduits and closed pipes.

Starting work with the project in SWMM 5.0 there is a possibility to choose one of the available units of flow intensity, described in Table 5.1.

Table 5.1. Flow intensity units available in SWMM 5.0

System of units	Symbol	Units
US	CFS	feet ³ s ⁻¹
	GPM	gallon s ⁻¹
	MGD	Megagallon day ⁻¹
SI	CMS	m ³ s ⁻¹
	LPS	litre s ⁻¹
	MLD	Megalitre day ⁻¹

5.4.3 Network drawing

After setting default properties, it is the right time to draw the sewer system. This chapter presents the rules of applying the objects into Map (Figure 5.3).

While drawing, toolbar showed in Figure 5.6 is used.

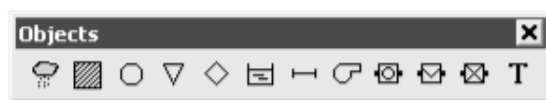













Fig. 5.6. Drawing objects toolbar

In order to create the network in SWMM 5.0 at first it is necessary to apply individual objects in appropriate places on the map. This is done only in an approximate way, since the program does not allow to enter coordinates at the time of drawing. Giving specific coordinates to junction points is possible while editing. In order to do this, select the object by double click of mouse, or by selecting it from Browser panel (see Figure 5.3), and then edit the coordinates (X-, Y-Coordinate).

While drawing Subcatchment area it is necessary to select  from drawing objects toolbar (Fig. 5.6) by clicking on it with the left mouse button in order to activate it. Then, outline the shape of subcatchment area. Select the vertices of polygon with the left mouse button, and then the right mouse button or “Enter” finishes subcatchment’s drawing. As before drawing, objects prefixes in *Defaults* has not been introduced, they can be given by selecting Editor Property with double-click on an individual object, and then writing needed prefix in Name. At the beginning of drawing junction points, select  *Junction* from the drawing toolbar, and then, with left mouse button place it in the right place on the map. SWMM 5.0 has also other junction points such as:  *Outfall*,  *Storage Unit*,  *and Divider*.

When applying Outfall  on the map, it need to be remembered that it is the last point of the system, and thus can be connected to just one side. After the application

of junction points, connections in the form of open conduits or closed pipes can be drawn. In order to do these, select  from drawing toolbar *Conduit*, and then mark, according to the flow direction, two junction points that are going to be connected.

In SWMM 5.0 drawing the following objects:  *Pump*,  *Orifice*,  *Weir*,  *Outlet*, is carried out in an analogous way as drawing connections. Connections shape in SWMM 5.0 can be selected in editor of connections' characteristics (Conduit) (described in 5.4.4). Program has also possibility to create irregular shapes of open conduits. Description of the conduit irregular shape can be done through unwinding *Shape* option in the Editor of Connections Properties (Fig. 5.7)

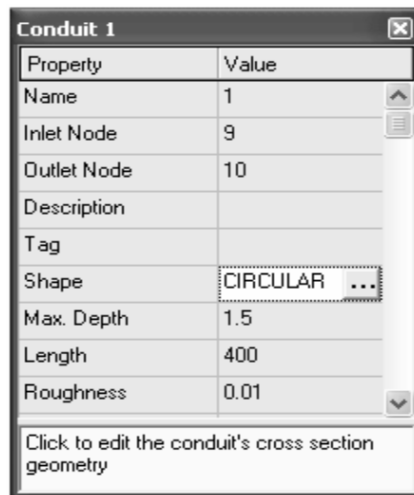


Fig. 5.7. Editor of Links Properties

Unwinding of this option will activate the following window (Fig. 5.8.):

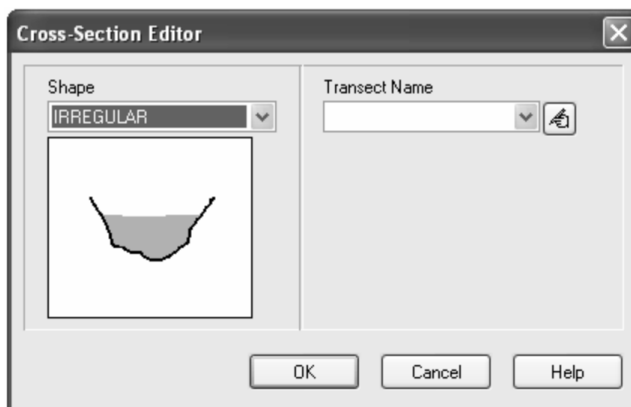

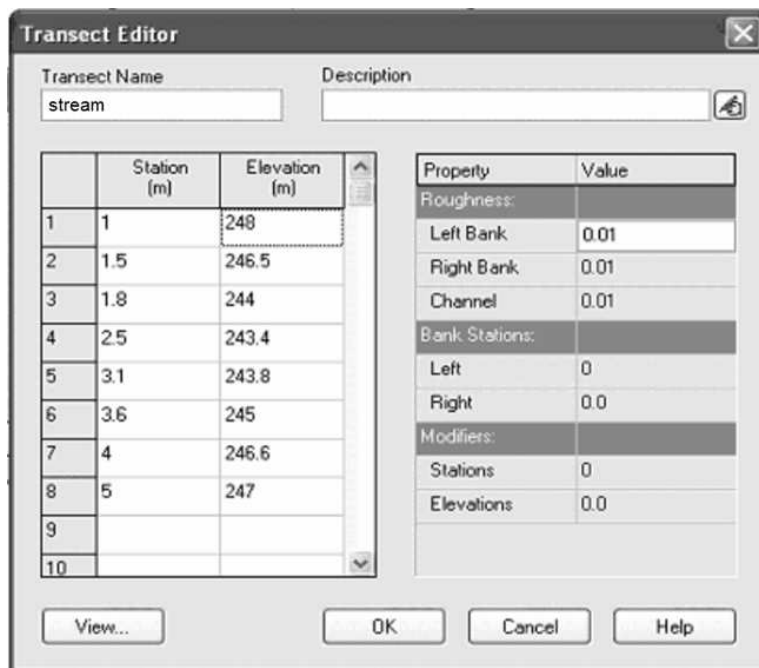



Fig. 5.8. Connections' Cross-Section Editor

In newly opened window showed in Figure 5.8 by unwinding *Shape* menu, any shape of conduit can be selected. If there is a need to create irregular shape of conduit, *Irregular* should be marked in this window. Then, click edit icon  showed in Figure 5.8 that will allow to describe conduit's cross-section shape in newly unwinded window (Fig. 5.9).



Transect Editor

Transect Name: stream Description: 


	Station (m)	Elevation (m)
1	1	248
2	1.5	246.5
3	1.8	244
4	2.5	243.4
5	3.1	243.8
6	3.6	245
7	4	246.6
8	5	247
9		
10		

Property	Value
Roughness:	
Left Bank	0.01
Right Bank	0.01
Channel	0.01
Bank Stations:	
Left	0
Right	0.0
Modifiers:	
Stations	0
Elevations	0.0

View... OK Cancel Help

Fig. 5.9. Irregular conduit cross-section editor

Newly opened window showed in Figure 5.9 will have no data placed in *Station*, *Elevation*, and *Transect name*, however data connected with Manning roughness coefficient located on the right part of the window are derived from the value entered in *Default*. Conduit roughness can be edited by assigning appropriate values for the left or right edge, or for the conduit bottom. For the data shown in Figure 5.9, there was depicted cross-section shape possible to show by selecting *View*.

In the development of storm water and combined sewer system model, crucial element is to describe precipitation over given subcatchment.  *Rain Gage* is used to do this. It is chosen from the objects drawing toolbar (Fig. 5.6). After selecting, the object is applied to any point on the map. When calculating, object location is not of importance, what matter is only subcatchment to which it is assigned.

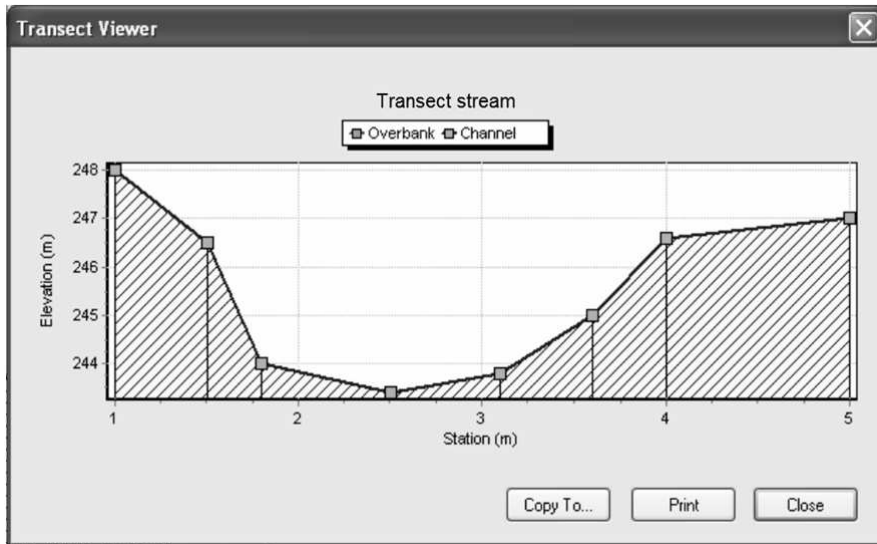


Fig. 5.10. View of created channel transect

In SWMM 5.0 there is possibility to use curve drawn connection, which can actually reflect, for example, river meanders or arcs of closed pipes. This is done by selecting one chapter which is going to be edited, then after marking this connection, click on the right mouse button, and then *Vertices*, which will change the cursor on . Next, once again click on connection with right mouse button and select *Add vertex* from menu. After that, the added vertex can be moved in any direction. If junction point has been already located not in the wanted place, it can be moved by clicking with the left mouse button and dragging into the right place. This operation can be done only when the cursor is active on the toolbar (Figure 5.3). The shape of catchment surface can also be edited. In order to do this, the particular subcatchment is selected by clicking with the left mouse button in its centre. Then, click with the right mouse button and in menu choose *Vertices*. Afterwards, in a manner similar in curving connections, subcatchment shape can be edited. There is also a possibility to add or remove the vertex.


In SWMM 5.0, surface runoff from subcatchment surface can be drained to the selected junction point such as: *Outfall*, *Storage Unit*, *Divider* or to other subcatchment. Graphically it is presented by an intermittent line representing the flow line. In order to create this line it is necessary to determine junction point receiving surface runoff from a given subcatchment. This is done in Subcatchment Properties Editor. It is precisely described in Chapter 5.4.4.

A major convenience while drawing sewer system in SWMM 5.0 is function *Convert to* and *Reverse*. The first option makes easier changing, for example, *Junction* into other junction point represented by *Outfall*, *Storage Unit*, *Divider*, or vice

versa. It is also possible for the links and nodes such as: *Conduit*, *Pump*, *Orifice*, *Weir* and *Outlets*, which can be exchanged between them. By using this function, network shape can be adjusted efficiently, avoiding such activities as: removing unnecessary objects and drawing new in their places. *Reverse* option is used to change flow direction in connections. After using, start and end junction point is being interchanged.

5.4.4 Enter the properties of hydrotechnical, and hydrological-climatic objects

After drawing the network, the next step in creating project ought to be introducing properties for each object within the network. When describing this Chapter, objects were divided into hydrotechnical – *Junction*, *Outfall*, *Divider*, *Storage units*, *Conduit*, *Pump*, *Orifice*, *Weir*, *Outlets*, and hydrological-climatic including *Sub-catchment*, *Rain gage*, *Aquifer*, *Groundwater* and *Snow pack*. Dragging objects into the map, SWMM 5.0 assigns them to specific features given in *Defaults* (Chapter 5.4.2). Object characteristics can be changed in the following ways:

- by double-clicking on an object on the map,
- by right-clicking on an object, which unwinds menu, then *Properties* should be selected,
- selection of an object from *Browser panel* (Fig. 5.4), then object edition by choosing  *Edit Object* in *Browser panel*.

More information on the properties of given object is received by clicking “F1” when *Editor property* is unwinded.

Describing properties of hydrotechnical objects

- Edition properties of *Junction* .

In SWMM 5.0 *Junction* are points, which connect the links one to another. In fact, they can represent a combination of natural open conduits or drains. Junction properties editor is presented in Figure 5.11.

Inflow – this option is used to describe the external supply of additional stormwater, wastewater, water infiltrating into the system, or sediments to a given junction. Three kinds of inflows can be chosen: *Direct*, *Dry weather*, *RDII*. This function is necessary in creating the project of combined system, or sanitary one.

Treatment – this function is used to describe properties of contaminant removing in junctions.

Max depth – maximum depth of conduit filling (diameter).

Surcharge depth – depth in junction over the maximum state for which there is not yet flood occurs (m).

Property	Value
Name	19
X-Coordinate	7768.420
Y-Coordinate	6736.840
Description	
Tag	
Inflows	NO
Treatment	NO
Invert El.	1010
Max. Depth	3

Click to specify any external inflows received at the junction

Fig. 5.11. Junction properties editor

Ponded area – function allowing for determining the retention surface for junction, on which wastewater, which flowed from drain, will be temporarily stored. Then, they will be re-introduced into the sewer system, when wastewater level stabilizes. This surface should be provided when *Allow ponding* option is selected. It can be found through: *Option* → *General* in the Browser panel (Fig. 5.3) (m²).

In SWMM 5.0 junction points are also *Outfall*, *Divider* and *Storage Unit*. Properties described for junction, from the name to the retention surface, for the abovementioned junction points are the same. Below are options for *Outfall*, *Divider*, and *Storage Unit* that junction does not have.

- Edit *Outfall* properties.

This object is treated as the final junction point in the sewer system. It ought to be remembered that outlet can be connected with pipe one side only.

Tide gate – outlets can be equipped in *Tide gate*. If wastewater level in the place to which it can be introduced is higher than wastewater level in sewer system, then reverse stopping flap breaks inflow from the outside into the sewer system. Only when wastewater level in sewer system is higher than its level outside, runoff from sewer system can occur. This prevents the reverse flow. If outlet is needed to be equipped in a flap, select in outlet properties editor from *Tide gate*, if flap is not necessary, select “No”.

Type – giving outlet type, boundary conditions are set for it. SWMM 5.0 offers 5 types of outlets: *Free*, *Normal*, *Fixed*, *Tidal*, *Time series*.

In the case of stabilized water state in the receiver (Fixed), there is necessary to give its height. This parameter is introduced into *Fixed stage*. After select of the variable state of water in the receiver (Tidal), this changeability ought to be described. It is given in unwinded window *Curve Name*, in which water level in the receiver is described for each hour.

- Edit *Divider* properties.

It is a junction point in sewer system which divides inflows into described out-flow pipe into a certain way, characteristic for the type of divide chamber (*Divider*). It works only in the calculation of kinematic wave method, and is treated as a simple junction in the dynamic wave method. There is a possibility to select 4 types of *Divider*, differing in a way of sharing a supply: *Cutoff* – divides whole inflow above the defined value, *Overflow* – divides whole inflow above the capacity of inlet pipe, *Tabular* – after selecting this kind of chamber, division is executed on the basis of division curve created by the user, *Weir* – overflow division.

After selecting *Cutoff* division chamber, in *Cutoff flow* border flow value need to be inserted. Above this value, there will appear the divided flow. For *Tabular* chamber, after unwinding in *Curve name* properties editor, inflow and outflow values are inserted, which will describe the shape of curve division. For this kind of chamber, division will be executed with regard to shape of described curve as a function of total inflow. For *Weir* chamber, in property editor insert minimal flow that will trigger a division (*Min. Flow*), flow depth (*Max. Depth*), coefficient of overflow outflow (*Coefficient*), which values are presented in the further part of this Chapter to describe *Weir* properties.

- Edit *Storage Unit* properties.

Chambers are junction points to store wastewater volume. They can represent either very small chambers or larger storage units like ponds. They can also be used to capture the peak of flood wave.

Evap Factor – values from “0” to “1” describe the degree of evaporation form the chambers surface. “1” in this case means total evaporation, while “0” its absence.

Shape curve – this option is used to describe the shape of chamber. User has a possibility to choose to methods: *Functional* and *Tabular*.

After choosing *Functional* the surface of chamber is calculated from below formula (Rossman, 2010):

$$A_c = a \cdot h_c^b + c \quad (5.6)$$

where: A_c – the surface of chamber (m^2), h_c – chamber depth (m), a – coefficient value in the functional relationship between surface area and storage depth, b – exponent value in the functional relationship between surface area and storage depth, c – constant value in the functional relationship between surface area and storage depth.

When the user decides to choose *Tabular* method to describe the shape of chamber, then *Curve name* window needs to be unwind, and next in newly appeared *Storage curve editor Area* corresponding to the points of chamber depth, should be described. On this basis, the program will estimate chamber volume. This curve is called in *Curve name*, and in the standard way assigns it in *Curve name* in the editor of chamber properties.

- Edit of *Conduit* properties.

In SWMM 5.0 links are treated as closed pipes or open conduits, which connect two junction points. By means of connections, wastewater is transported from one place to the another.

Inlet node – so-called “upper drain”, from which wastewater is entered into a connection.

Outlet node – so-called “bottom drain”, into which wastewater is supplied.

Max. Depth – maximum height of filling for given connection (m).

Roughness – Manning’s roughness coefficient for open conduits or closed pipes. Values of these coefficients are placed in the Help menu of the program in tab *Conduit properties* (-).

Inlet offset – at this point, enter the difference of ordinate height for the bottom of conduit and drain at the “upper drain” (m).

Outlet offset – at this point, enter the difference of ordinate height for the bottom of conduit and drain at the “bottom drain” (m).

Initial flow – initial wastewater flow rate in the pipe, before calculations (chosen unit of flow rate).

Maximum flow – value of maximum allowable flow in the pipe that will not be exceeded during simulation. This value can be entered for the dynamic wave method (chosen unit of flow rate).

- Edit *Pump* properties.

Pumps are used to transport wastewater to the places located on higher ordinate where gravitational flow would be impossible.

Inlet node – so-called “upper drain”, from which wastewater is pumped, is defined.

Outlet node – so-called “bottom drain”, to which wastewater is pumped, is defined.

Pump Curve – unwinding this window is necessary to select one of the four available pump types, in *Pump type*. In the editor of pumps characteristics, properties of pump, depending on its type, are necessary to be introduced. Then, it is assigned at *Pump Curve* window, in the editor of pump characteristics in a standard way.

There are the following available pump types:

Type 1 – Off-line: it is a pump of separable type with collective, dewatering drain. Efficiency of this pump depends on wastewater volume in collective dewatering drain. Pump works independently from the sewer system. When dewatering

drain is full, then its inflow yields. It is resumed when wastewater state in the drain is lower than before.

Type 2 – In-line: amount of pumped wastewater is depended on the height of drain filling, from which wastewater is pumped.

Type 3 – In-line: amount of pumped wastewater is depended on the height of amount of wastewater in “bottom” and “upper” drain.

Type 4 – In-line: type 4 pump efficiency is dependent on the height of drain filling from which wastewater is pumped. Flow is regulated on the basis of curve resulting from the application of points defining the level of wastewater and the flow rate. Figure 5.12 shows the characteristics of pump types available in program.

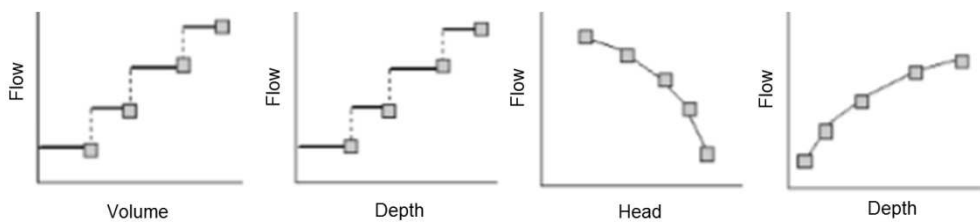


Fig. 5.12. Characteristics of pumps available in SWMM 5.0, from left: Pump of type 1, Pump of type 2, Pump of type 3, Pump of type 4 (Rossman, 2010)

- Edit *Orifice* properties.

This object in SWMM 5.0 is used to regulate wastewater outflow from junction points. In particular, it can be used as an outlet from the tank storing flood wave. The user has a possibility to choose either bottom outlet or the side one. This object can be used to simulate outflow from the tank either for kinematic wave model or dynamic one. If the object is not attached to the tank, then it can be used in calculations only for dynamic wave method.

- Edit *Weir* properties.

Overflows similarly to the holes are used to wastewater regulation between such objects as drains or tanks. They can be used to simulate outflow from the tank, either for the kinematic wave model or dynamic one. If the object is not attached to the tank, then it can be used in calculations only for the dynamic wave method. Overflows can also be located along the side of conduit. In the editor of overflow properties, *Name*, *Inlet node*, *Outlet node*, means the same as for the outlet.

Weirs, like orifices, are used to model outlet and diversion structures in a drainage system. Weirs are typically located in a manhole, along the side of a channel, or within a storage unit. They are internally represented in SWMM as a link connecting two nodes, where the weir itself is placed at the upstream node. A flap gate can be included to prevent backflow (Rossman, 2010).

Table 5.2. Equations describing consumption for various types of weirs in SWMM 5.0

Type of weir	Cross Section Shape	Flow Formula
transvers	rectangular	$C_w L_o h^{3/2}$
lateral	rectangular	$C_w L_o h^{5/3}$
triangular	triangular	$C_w S h^{5/2}$
trapezoidal	trapezoidal	$C_w L_o h^{3/2} + C_{ws} S h^{5/2}$

where: C_w – weir discharge coefficient ($\text{m}^3 \text{s}^{-1} \text{m}^{-n}$), L_o – weir length (m), h – head difference across the weir (m), S – side slope of V-notch or trapezoidal weir, C_{ws} – discharge coefficient through sides of trapezoidal weir ($\text{m}^3 \text{s}^{-1} \text{m}^{-n}$).

- Edit *Outlets* properties.

Outlets in SWMM 5.0 are devices used to control outflow from the drains or tanks. They can be used to simulate outflow from the tank, either in calculation kinematic wave or dynamic one. If the object is not attached to the tank, then it can be used only in calculations of dynamic wave method. In the editor of consumption regulators properties, *Name*, *Inlet node*, *Outlet node*, *Description*, and *Tag* have standard meaning. When the user decides to choose *Tabular* method to describe flow through the consumption regulator, then *Curve name* window needs to be opened, and in *Rating curve editor* some points of wastewater surface level, flow rate through the regulator is needed to describe. This curve should be named in *Curve name*, and in a standard way assign it in curve name at the editor of regulator properties.

Describing properties of hydrological-climatic objects

- Edit *Subcatchment* properties.

In SWMM 5.0, subcatchment is an area that receives rain or snow, which is then discharged to one of junction points or another subcatchment.

Property	Value
Name	6
X-Coordinate	-639.535
Y-Coordinate	8779.070
Description	
Tag	
Rain Gage	*
Outlet	*
Area	5
Width	500
User-assigned name of subcatchment	

Fig. 5.13. Editor of subcatchment properties

- Edit *Rain Gage* properties.

In SWMM 5.0 the *Rain Gage* option provides information on rain for given subcatchment area to which it is assigned. Data on the precipitation can be defined by the user or loaded into the program from an external file. In the editor of precipitation properties, options from *Name* to *Tag* have a standard meaning described in properties of subcatchment and junction. In tab *Data Source* the user can choose to load data describing precipitation directly (*Time series*) or to load precipitation value from the external file. The first case needs standard procedure of loading precipitation data by unwinding *Series name*. When data is loaded from the external file, in *File name* select source file from which data will be loaded. Then, in *Stadium ID*, identification number contained in source file has to be entered. There is a need to give a unit, in which source data is being loaded. It is done in *Rain unit*.

Aquifer and Groundwater

In developing the simulation of surface flow in open conduits, a very important element that could significantly affect obtained results, is taking into consideration flow of water infiltrating and exfiltrating from pipes. Activating *Aquifer* and *Groundwater* editor of properties is discussed while describing edition of subcatchment properties.

In SWMM 5.0 the aquifer is used to describe vertical movement of water infiltrating from subcatchment surface to which particular aquifer is assigned. It also describes groundwater infiltration into the sewer system, and exfiltration as well. The user can assign the created aquifer to one or more subcatchment surface. Values concerning hydraulic conductivity, depending on the type of soil, withering plants, field capacity and porosity, are available in help menu of SWMM 5.0 in *Soil characteristic*.

Groundwater flow is calculated from the following formula (Rossman, 2010):

$$Q_{gw} = A_1 (H_{gw} - H^*)^{B_1} - A_2 (H_{sw} - H^*)^{B_2} + A_3 (H_{gw} - H_{sw}) \quad (5.7)$$

where: Q_{gw} – groundwater flow ($\text{m}^3 \text{ha}^{-1}$), H_{gw} – height of saturated zone above bottom of aquifer (m), H_{sw} – height of surface water at receiving node above aquifer bottom (m), H^* – threshold groundwater height (m).

Other items from the formula 5.7 are described below.

Groundwater flow coefficient – value of A_1 coefficient, in formula to calculate groundwater flow. It is a multiplier to the difference of ordinate of groundwater and junction bottom that receives inflow.

Groundwater flow exponent – B_1 value from the formula on groundwater flow.

Surface water flow coefficient – A_2 value.

Surface water flow exponent – B_2 value.

Surface groundwater interaction coefficient – A_3 value.

Fixed surface water depth – set depth, at which wastewater mirror is located in junction point receiving inflow (Receiving node). Leave 0 if this depth is to be variable in time, and determined during flow calculations. In the formula on groundwater flow it is H_{sw} (m).

Threshold groundwater elevation – ordinate of groundwater elevation (bottom elevation + water table elevation) that must be reached when the flow of groundwater is going to occur. If this position is not filled, then ordinate of junction bottom receiving inflow is assumed in calculations. It is represent as E in the formula on flow rate (m above sea level).

Editing of *Snow pack* properties is significant when it is necessary for the combined and stormwater system to take into account additional part of flow originating from melting snow. Activation of *Snow pack* properties editor is discussed while describing subcatchment properties editing. Editor window of snow layer consists of two tabs: *Snow pack parameters* and *Snow removal parameters*. In the first tab, parameters values are entered for three different types of surface: *Flowable*, *Impervious* and *Pervious*. The minimum and maximum value of snow melting coefficient is used to estimate general coefficient describing snow melting for each day in a year. This general coefficient of melting is used to calculate melting rate. In order to fully represent the issue concerning snow melting, parameters included in *Snow melt* of climatic option editor, should also be described. To describe this parameter, with *Data* selected in a browser, choose *Climatology* → *Snow melt*. After these activities window showed in Figure 5.14 will activate.

The image shows a software dialog box titled "Climatology Editor" with a close button (X) in the top right corner. It contains five tabs: "Temperature", "Evaporation", "Wind Speed", "Snow Melt" (which is currently selected), and "Areal Depletion". The "Snow Melt" tab displays a list of seven parameters, each with a corresponding text input field to its right:

- Dividing Temperature Between Snow and Rain (degrees C)
- ATI Weight (fraction)
- Negative Melt Ratio (fraction)
- Elevation above MSL (meters)
- Latitude (degrees)
- Longitude Correction (+/- minutes)

At the bottom of the dialog box, there are three buttons: "OK", "Cancel", and "Help".

Fig. 5.14. Climatology Editor – *Snow melt* tab

5.4.5 Simulation


After drawing the sewer system and introducing the properties of the objects included in it, the appropriate calculations can be performed. This is done by clicking the following icon  located on the toolbar (Fig. 5.15) or by selecting *Main Menu* → *Project* → *Run simulation*. Calculation correctness and precision of obtained results are showed in *Run status* displayed after the simulation (Fig. 5.15).



Fig. 5.15. Calculation status – correct

Continuity error informs about errors indicated in the volume balance. When the error is about $\pm 7\%$ for large systems and $\pm 3\%$ for smaller ones, then simulation should be performed for shorter time step, or the result after correction of connection length of junction points should be checked. There is also a possibility to check the continuity errors in *Status report*, which can be seen after simulation. They are available in main menu (Fig. 5.1) in *Report* → *Status*. All calculated data on the sewer system are included here. In a situation, when the sewer system is described in incorrect way, preventing proper calculations, after attempt to perform calculations the following message appears (Fig. 5.16).



Fig. 5.16. Calculation status – incorrect

After clicking OK status report appears that informs about errors occurring during calculations (Fig. 5.17). Reported errors have been marked by the numbers, and their detailed description is given in SWMM 5.0 User's Manual in the appendix.

Performing the correct calculations by SWMM 5.0 requires not only creating the proper scheme of sewer system with introducing in editor relevant properties of the objects, but also significant element is selecting appropriate time step (s) for which calculations are made.

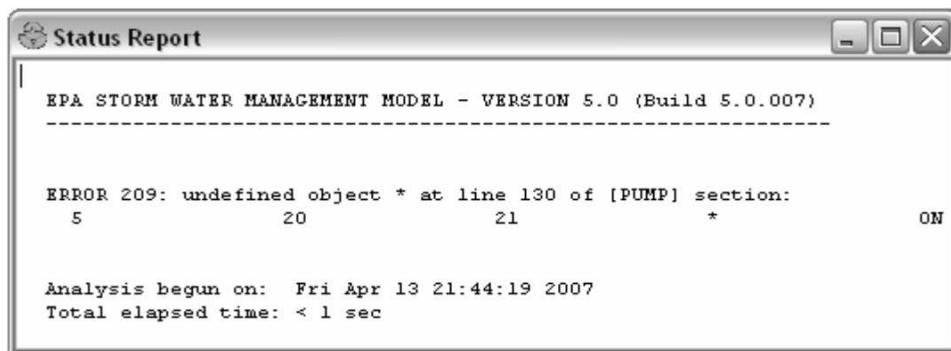


Fig. 5.17. Exemplar errors report

Time step is chosen by selecting from the browser (Fig. 5.3) at marked tab *Data Option* → *Time step*. This will activate the following window (Fig. 5.18):

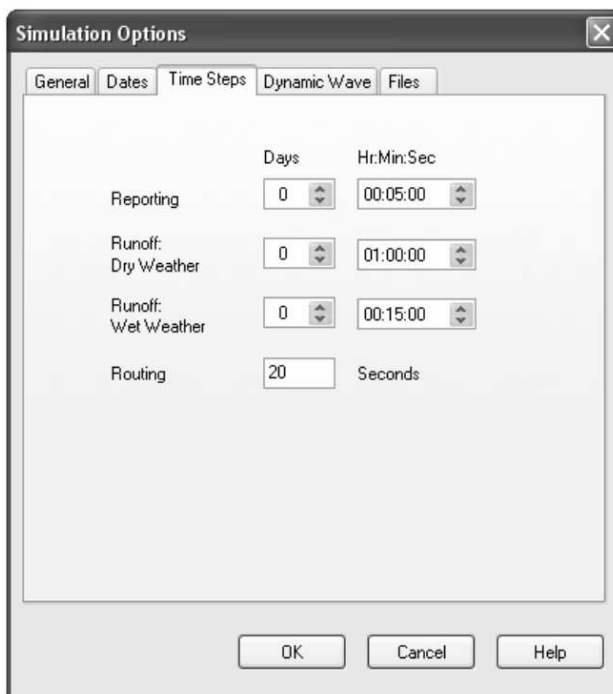


Fig. 5.18. Simulation time options

The choice of time step for calculations is made at *Routing*. Sufficiently long time step can be determined from the following formulas (Rossman, 2010):

- for connections:

$$t \leq \frac{L_c}{(g \cdot D_c)^{0.5}} \quad (5.8)$$

where: Δt – calculations time step (s), L_c – connection length (m), g – acceleration of gravity (m s^{-2}), D_c – maximum wastewater depth in connection (m).

When this condition is met, then dynamic wave is able to spread to all length of connection.

- for junctions:

$$\Delta t \leq \frac{C \cdot A_s \cdot \Delta H_{\max}}{\sum Q} \quad (5.9)$$

where: Δt – time step of calculations (s), C – constant equal 0.4 received on the basis of SWMM 5.0 work experience, ΔH_{\max} – maximum change of wastewater level for time interval (m), A_s – subcatchment area per junction (ha), $\sum Q$ – sum of network supplies to junction.

Calculations should be carried out for the most unfavourable conditions, that is for the shortest connection having the smallest cross-chapter diameter into which the greatest amount of wastewater flows. Based on the SWMM 5.0 work experience, it was found that 20-second time interval is almost always adequate to obtain correct calculations (Rossman, 2010). To simulate the analysis of runoff quality, there is required the smaller time step of about 5 (s).

Instability in the numerical calculations in SWMM 5.0 usually occurs in the following situations:

- Lack of wastewater in junction despite the fact that for a given junction point constant or variable supply is determined. The reason of this is too big time step and runoff from given junction point to the bottom of the system. This problem can be eliminated by reducing the time step of calculations.
- High speeds in the system.

It is also recommended to avoid connection of many hydrotechnical devices such as pumps, overflows, outlets, consumption regulators or holes to a single junction point.

5.4.6 The calculation option

Hydraulic and hydrological calculations made in SWMM 5.0 are based on the principle of mass, energy and momentum conservation. While making the calculations, program bases on the final elements method (Rossman, 2010). Described program can calculate the flow using three alternative methods: dynamic wave routing, kinematic wave routing, and steady flow routing.

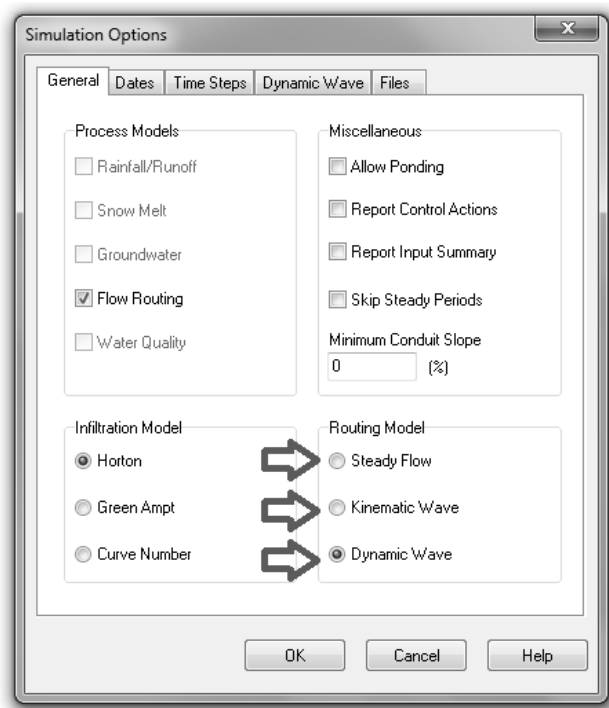


Fig. 5.19. Layout of choosing the method to calculate the flow intensity based on SWMM 5.0 screen

Steady flow rate

The first of the offered methods is steady flow rate. The calculation procedure is in a way somewhat idealized, but on the other hand, very simplified. It assumes in advance that in each calculation time step, the flow is uniform and steady. In this way, flow from the top to the bottom of the pipe is constant. Steady flow routing does not include the channel retention, changes of flow direction and the flow under pressure, accumulation, pressure losses at the channel outlet and inlet. It can be used in the branched system, in which each junction has only one outlet channel. This method can provide the first approximation for the initial analysis using long-term continuous simulations (Rossman, 2010).

Kinematic wave routing

Another option to calculate is the kinematic wave routing. The Saint-Venant equation is used in this method together with the flow continuity equation. However, calculations are simplified by omitting the inertia and hydrostatic force (Mitosek, 1999).

In this method, the surface of wastewater drop is equal to the channel decrease. However, this method takes into account in calculations the situation in which the

excess of flow escapes outside through the drain, and may be retention until the wastewater decreases in the pipes. Then, it is inserted back into the sewer system. However, this method does not take into consideration the flow accumulation, pressure losses at the channel inlet and outlet, changes in flow direction, and pressure flow (Rossman, 2010). This method can be used in a branched system, and also for moderately long time steps, from 5 to 15 minutes.

Dynamic wave routing

The last option of the flow calculation is the dynamic wave routing. Model of a given solution also uses the Saint-Venant equation, but this time conjugated with the flow continuity equation (taking into account the boundary conditions). Thus, the method for calculations uses system of first order differential equations describing the transient slowly-variable motion. This method takes into account the flow under pressure, and situation when the excess of flow escapes outside through the drain, and can be retention until the decrease of wastewater in pipes. Then, it is inserted back to the sewer system. Dynamic wave routing takes into account channel retention, flow accumulation, change of flow direction, losses at the inlet and outlet if the channel. It can be applied to branched and ring networks. The method ought to be chosen for systems undergoing the phenomenon of deposits accumulation, due to a limitation of gravity flow or by adjusting it via overflows, consumption regulators, and outlets. This method provides the ability to use small time steps, which are often necessary for reliable analysis (1 min time steps) (Rossman, 2010). It is usually the most complicated method of calculation available in the program, but so that it provides the most accurate reflection of the modelled network.

5.4.7 Results and their presentation

As a result of calculations, the values of basic flow characteristics changes (flow intensity and filling) in the individual elements are obtained. The results take the discrete forms, which means that information is available only in selected areas of the system and consecutive time steps. The calculations results allow to track changes in time such as flow intensification, filling, flow rate, the quality indicators in junctions and in the middle section of the channel length (Skotnicki, 2005; Rossman, 2010).

Forms of displaying results are as follows:

- results in map window – see Fig 5.3 and chapter 6.2.1,
- graphs that can be used to get information in a quick way about the relations that exists between arbitrarily selected parameter, or how one parameter changes in time – see chapter 6.2.2 and Fig. 6.7,
- results presented as tables – for more detailed description see chapter 6.2.3,

- animation, by means of which it is possible to dynamically depict simulation results – see chapter 6.2.4 and Fig. 6.8,
- longitudinal profiles of modelled network, which can be combined with animation showing changes in the position of the wastewater surface in the channels during the simulation – see chapter 6.2.5 and Fig. 6.10,
- presentation of results by status report – see chapter 6.2.6 and Fig. 6.11.

Advantages and disadvantages of SWMM 5.0

As the main advantages of SWMM 5.0 following can be mentioned (*Zawilski and Sakson, 2008*):

- ability to check the sewer systems functioning for a wide variety of options,
- ability to create models for sanitary sewers, storm water system, and combined sewer system, both for the branched and ring systems,
- wide range of calculation methods choice, both for flow and infiltration,
- large selection of channel shapes, and the possibility to create open troughs,
- clear visualization of results,
- ability to solve many problems in the field of hydraulics and hydrology,
- no costs associated with the purchase of the program.

The main noted disadvantages of SWMM 5.0 are:

- inability to print the image from the program main map window in a particular scale,
- possibility of temporary errors occurrence while working in the program, which after switching off and on of the program recede,
- many of tabulated parameters available in help menu, necessary in development of the model, are described in U.S. units,
- it does not allow for direct storing of calculation results, such option appears only while trying to exit the program,
- a large practical disadvantage is lack of ‘back command’ also known as “redo command”, which forces the user to careful attention during working with this program.

6 Exemplary design of stormwater system with SWMM 5.0

6.1 Description of simulated stormwater system

The exemplary project of storm water system performed by the dynamic wave model for LPS unit, allowing to rehearse the earlier described capabilities of SWMM 5.0 will be presented in this chapter (Karpiuk and Jarosławski, 2007). The main task of the designed network is to transport the storm water of surface runoff derived from the GR1 rainfall event and three separate subcatchments. The first subcatchments, marked as S1, has an area of 3 (ha), width of 200 (m), inclination of 1%. The surface runoff is being directed to junction J1. The area of subcatchment is consisting of 25% of impervious surface, made of smooth concrete, for which Manning's coefficient equals to $0.012 \text{ (s m}^{-1/3}\text{)}$ and arable land characterized by $n=0.013 \text{ (s m}^{-1/3}\text{)}$. The surface retention depth for impervious area is equal to 0.0017 (m) and for the pervious area 0.004 (m). The Horton method of infiltration calculation is going to be applied to the model. The S1 subcatchment is located on silty soil for which infiltration rate varies in range of 3.3–76.2 (mm h^{-1}). The remaining input data for Horton's model of infiltration are: decay rate equals 3.0, drying time 7.0. Characteristics of soil required to description of infiltration are available in menu by *Horton infiltration parameters*. Fig. 6.1. presents the editor of subcatchment properties after inputting all the necessary data.

The properties of S2 differ from S1 only by the area equal to 2.5 (ha), width of 200 (m), inclination 0.5% and 18% of impervious area. The surface runoff is directed to J2 junction. The properties of S3 subcatchment are as follows: outflow to J1 junction, area of 2 (ha), width of 150 (m), 30% of impervious area, Manning's coefficient for impervious surface $n=0.011$ (smooth asphalt), Manning's coefficient for pervious surface $n=0.24 \text{ (s m}^{-1/3}\text{)}$ – dense grass, the surface retention depth for impervious area is equal to 0.0015 (m) and for the pervious area 0.005 (m), Horton's model of infiltration, clay soil, infiltration rate 0.254–50.8 (mm h^{-1}), decay rate 4 and drying time 12. The plastic pipes of Manning's coefficient $n=0.013 \text{ (s m}^{-1/3}\text{)}$ were applied to network construction. All pipelines are aligned with the inclination of 4‰. The lengths of pipes: C1=100 (m), C2=90 (m), C3=90 (m), C4=130 (m). Pipelines C1, C2, C3 have the circular shape of cross section while C4 has an egg-shaped cross section. The maximum heights of cross section are C1=0.4 (m), C2=0.3 (m), C3=0.6 (m), C4=0.7 (m). The C4 was equipped with a flap gate. The elevation of junction bottom is lower by 0.1 (m) from the elevation of pipe bottom for pipelines C1, C3, C4, excluding the outfall junction. In case of pipeline C2 the difference of elevation between the upstream junction bottom and pipeline bottom equals to 0.1 (m), while the same difference for the bottom of downstream junction and pipeline bottom is equal to 0.2 (m). The input data concerning geometrical characteristics of junctions are presented in table 6.1.

Property	Value
Name	S1
X-Coordinate	1443.218
Y-Coordinate	7823.344
Description	
Tag	
Rain Gage	GR1
Outlet	J1
Area	3
Width	200
% Slope	1
% Imperv	25
N-Imperv	0.012
N-Perv	0.13
Dstore-Imperv	0.0017
Dstore-Perv	0.004
%Zero-Imperv	25
Subarea Routing	OUTLET
Percent Routed	100
Infiltration	HORTON
Groundwater	NO
Snow Pack	
Land Uses	0
Initial Buildup	NONE
Curb Length	0

Infiltration parameters (click to edit)

Fig. 6.1. S1 subcatments properties editor

Table 6.1. Characteristics of junctions

	J1	J2	J3	J4	J5
Bottom elevation (m above sea level)	100	99.96	99.6	99.24	100.5
Max depth (m)	2.2	2.1	2.5	3.0	2.5

The remaining last nodal point of the network is the free outfall (marked as Out1). The elevation of outfall bottom is 99.98 (m above sea level). The storm waters are transported from junction J4 to a storage tank of bottom elevation equal to 101.5 (m a. s. l.). The maximum depth of the storage tank is 3 (m), the shape of the tank is described by tabular function reflecting the relation between the depth of tank and the area of sewage cross section – see Fig. 6.2.

Storm water is transported to the tank by a pump of TYPE 4, with the initial status set as ON. The curve presenting the characteristics of the pump is described as relation of storm water depth to flow rate. The values applied to the characteristics are presented in Fig. 6.3 – left, while the characteristic is shown at the right side.

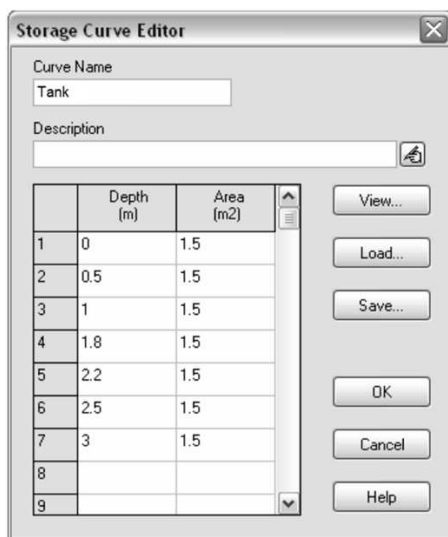


Fig. 6.2. Storage tank curve shape editor

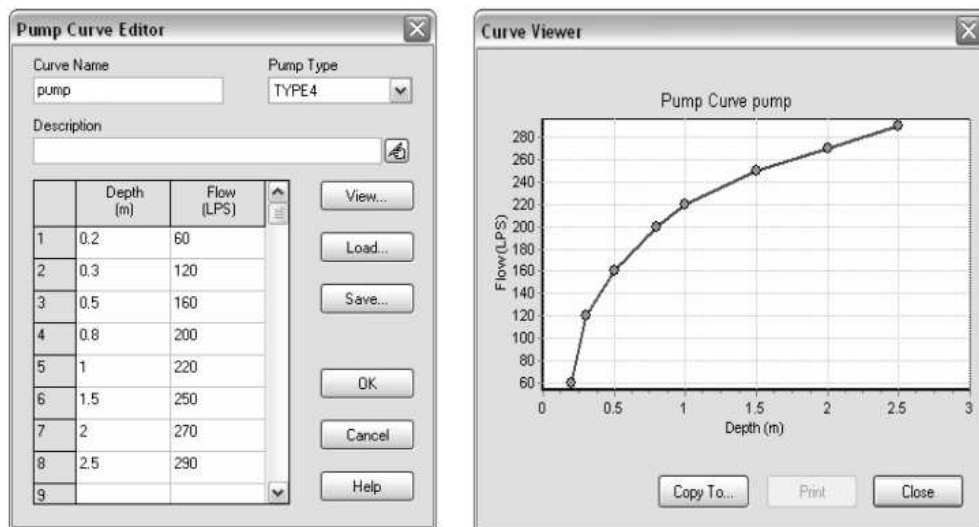


Fig. 6.3. Editor of pump characteristics (left), pump characteristics (right)

Outfall from the tank is regulated by the circular side outlet, marked as R1, of diameter 0.3 (m) and outflow coefficient 0.65.

The studied network will be tested for the rainfall event of time duration 2 (hr) and rainfall height 47.5 (mm). The rainfall intensity during the first hour of simulation was equal to 0 (mm h^{-1}), between 1st and 2nd 35.1 (mm h^{-1}) and between 2nd and 3rd 12.4 (mm h^{-1}). Fig. 6.4 presents the modeled storm water network.

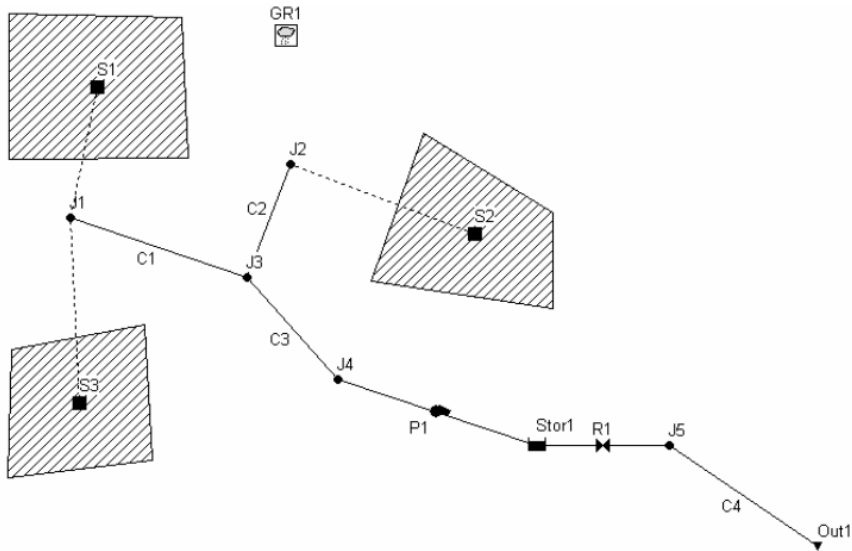


Fig. 6.4. The scheme of modelled storm water network

The presented network will be tested for the dynamic wave model with LPS (Tab. 5.1) as flow units, time step length 15 s and total time of simulation 4 hours.

6.2 Visualization of simulation results

This chapter contains various possible manners of the obtained results visualization. The results of calculation may be presented as maps, graphs, tables, profiles or state reports.

6.2.1 Results in a map window

One of the possible manners of result and input data for subcatchments, lines and junctions presentation is visualization on the map supported with the legend. The legend presents the intervals of values describing the selected physical parameter. The more precise reading of the applied parameter in SWMM 5.0 is possible by *Annotation* function available in main menu under *View* → *Map options* or by the direct RMB click in the map window (Fig. 5.3.) and then selecting *Options* from the menu which opens the window shown in Fig. 6.5.

Figure 5.6. shows the developed *Annotation* window in which, in field No. 1 it is allowed to set the IDs and values for subcatchments, links, nodes and rainfall events (rain gauges). It is also possible to change font size for IDs and values (by *Font Size*). The remaining menu items visible in the field marked as No. 2 allow graphical filling of subcatments area, determining the size of node representing junctions and thickness of line representing pipelines, arrows showing direction of flow and finally the color of map's background.

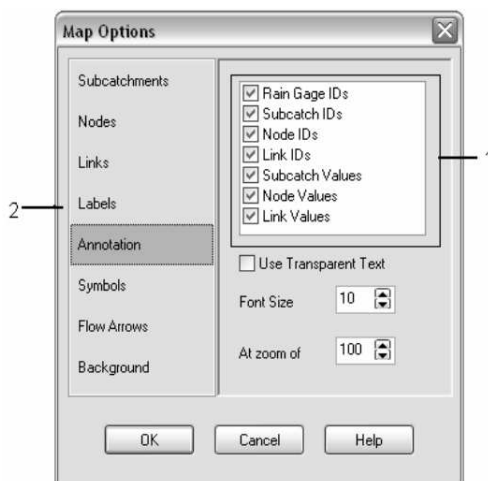


Fig. 6.5. Map options editor – Annotation

6.2.2 Presentation of results as graphs

The results of simulation and the selected parameters describing nodes, links and subcatchments or various phenomena occurring during the storm water network operation, e.g. snow cover, precipitation, nodal inflows may be presented as graphs. Settings allowing to show the above are available in the menu point *System*. The prepared graphs may be printed, copied to the clipboard or file as well as saved as metafile, bitmap and text files.

Presentation of results as graphs is available by selecting the main menu item *Report* → *Graph* → *Time series* or by using the proper icon. Fig. 6.6. shows the Time series plot editor in which time related changes of flow velocity for C1, C2, C3, C4 pipelines were set.



Fig. 6.6. Time series plot editor

The *Time series plot* settings editor presented in Fig. 6.6., after selecting OK, allows graphical presentation of time-varied flow velocity for selected pipes – see Fig. 6.7.

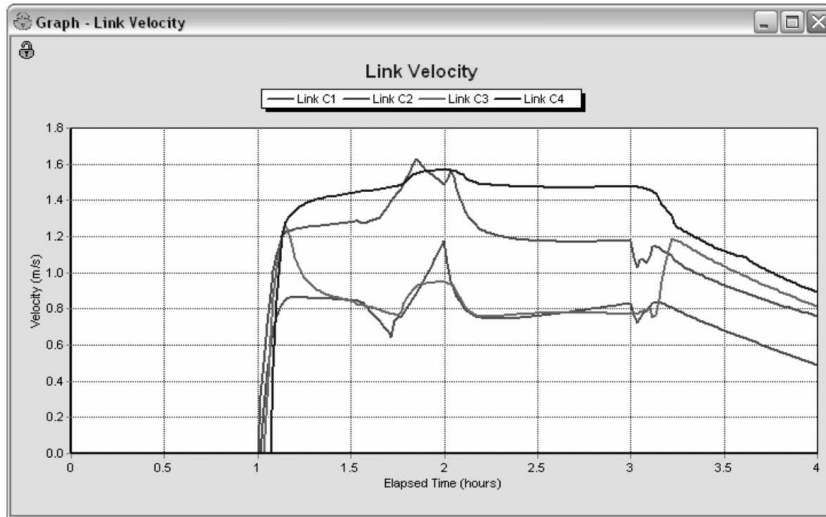


Fig. 6.7. Time dependant flow velocity for pipelines C1, C2, C3 and C4

SWMM 5.0 allows presentation of the following parameters as graphs:

- for subcatchments: precipitation (*Rainfall*), snow cover (*Snow depth*), total losses of evaporation and infiltration (*Losses*), surface runoff (*Runoff*), in-flow of groundwater to the system (*GW flow*), groundwater table elevation (*GW elevation*),
- for nodal points: storm water depth (*Depth*), height of storm water table (*Head*), volume of stored storm water (*Volume*), lateral inflow (surface runoff + all other external inflows) (*Lateral inflow*), total inflow (lateral inflow + upstream inflows) (*Total inflow*), flooding intensity (*Flooding*), concentration of each pollutant after any treatment (Washoff concentration of each pollutant),
- for links: flow rate (*Flow*), average water depth (*Depth*), flow velocity (*Velocity*), Froude number (*Froude no.*), ratio of depth to full depth (*Capacity*), pollutants concentration (*Concentration of each pollutant*),
- the remaining data available in *System* menu point: air temperature (*Temperature*), total rainfall (*Rainfall*), total snow cover (*Snow depth*), mean evaporation and infiltration losses (*Losses*), total runoff (*Runoff*), total dry weather inflow (*DW inflow*), total groundwater inflow (*GW inflow*), Total RDII inflow (*I&I inflow*), Total direct inflow (*Direct inflow*), total external inflow (*Total inflow*), total flooding (*Flooding*), total outflow from outfalls (*Outflow*), total nodal storage volume (*Storage*).

6.2.3 Presentation of results as tables

If a precise numerical values of the obtained results are required the presentation of the results as tables is available. Tables may be activated by the main menu item *Report* → *Table* and then *By object* for the selected object or *By variable* for the selected parameter. *By object* option allows to obtain the table containing several variables for one object only while *By variable* presents the values of the selected variable for the numerous objects of the same type.

Tables are also available by direct selection of *Table* icon from the toolbar, then selection *By object* or *By variable* from the drop menu.

Tabularized are presented for the time steps according to the report step determined in *Time step* options in *Reporting* in the *Data* browser menu item.

It is also possible to present all the parameters mentioned in the previous chapter for all subcatchments, nodes and links.

6.2.4 Presentation of results as animations

The SWMM 5.0 software allows the dynamic presentation of the results of simulation as animations, which can be activated and controlled by the main menu item *View* → *Toolbars* → *Animator* triggering display of Animator window (see Fig. 6.8.).

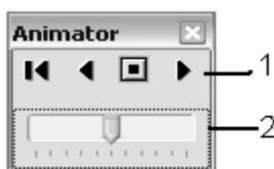


Fig. 6.8. Animator window

Animator window contains standard display buttons in the region No. 1 (Rewind, Back, Stop, Forward) and animation speed slider in area No. 2. To present time-variable changes of the studied object's parameter its required to select, at the Map window in the browser, the required option.

6.2.5 Profiles

The SWMM 5.0 contains the function allowing preparation of the longitudinal profiles of modeled network which option can be selected by the main menu item *Report* → *Graph* → *Profile* or by selection of the *Profile* icon. The *Profile plot* window is presented in Fig. 6.9.

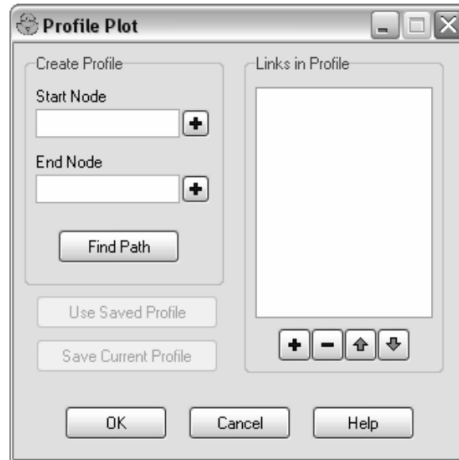


Fig. 6.9. Profile plot window

The longitudinal profile may be prepared by two methods. The first one is based on the direct assignment the links, in the window map, for which the profile is required by adding them to window *Links in profile* by *Insert link* icon. The second method relays on determination of the initial and final points of the profile by assignments of the proper points in *Start node* and *End node* of the profile, then the *Find path* should be introduced. The profile developed for the early prepared model, with starting point J1 and final point Out1, obtained by *Find path* including links C1, C3, P1, R1, C4 was presented in Fig. 6.10. This profile shows the wastewater depth for the second hour of the simulation for which the flooding from node J1 and total filling of C1 and C3 pipelines. The dynamic visualization of wastewater table may be achieved by application of animations.

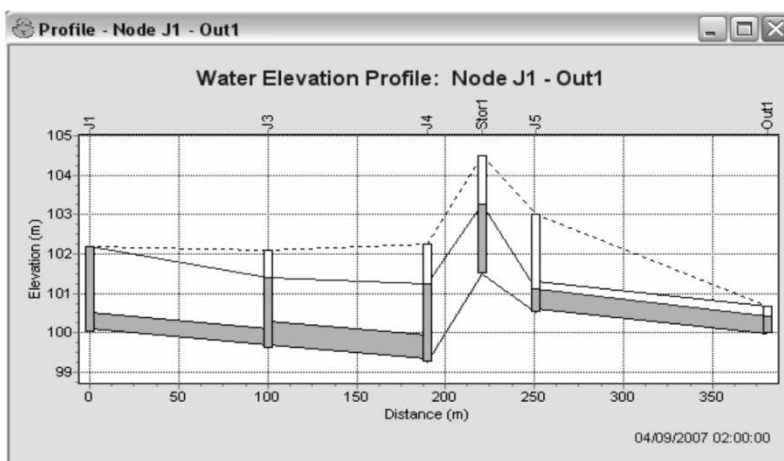
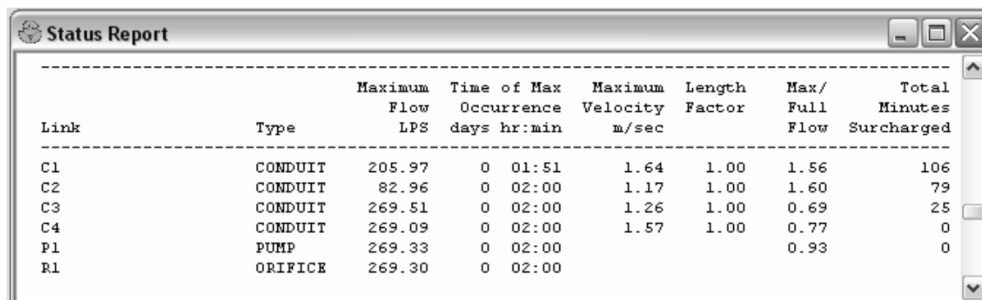


Fig. 6.10. Longitudinal profile of storm water system – links C1, C3, P1, R1 and C4

6.2.6 Presentation of results by status report

Status report available in the main menu *Report* → *Status* allows the number of interesting information concerning the modeled network. Fig. 6.11. presents the fragment of status report concerning joins (nodes).



Link	Type	Maximum Flow LPS	Time of Max Occurrence days hr:min	Maximum Velocity m/sec	Length Factor	Max/ Full Flow	Total Minutes Surcharged
C1	CONDUIT	205.97	0 01:51	1.64	1.00	1.56	106
C2	CONDUIT	82.96	0 02:00	1.17	1.00	1.60	79
C3	CONDUIT	269.51	0 02:00	1.26	1.00	0.69	25
C4	CONDUIT	269.09	0 02:00	1.57	1.00	0.77	0
P1	PUMP	269.33	0 02:00			0.93	0
R1	ORIFICE	269.30	0 02:00				

Fig. 6.11. Status report window

The status report contains information concerning: the selected unit of flow, method of flow calculation, time related input data, method of infiltration calculation and calculated characteristic parameters for joins, links and subcatchments.

6.3 Analysis of surface runoff quality

The SWMM 5.0 allows the chemical analysis of surface runoff and flow inside the pipelines. This problem will be presented on the exemplary combined sewage network created by application of previously developed model of storm water system with added inflow of sanitary waste water into J4 node – assignment of *Inflow* → *Dry weather inflow*. The value of inflow was set as $1 \text{ dm}^3 \text{ s}^{-1}$ in *Average value* window, which value was multiplied by *Multipliers* determined by the assumed *Time pattern*. Determination of time pattern requires designation of type of time pattern (monthly, weekly, daily, hourly), name of the time pattern and numeral value for the Multipliers. The hourly time pattern was selected to our exemplary modeling attempt and the hourly mean inflow of sanitary sewages were assumed as follows:

- 8:00–9:00 → $1 \text{ (dm}^3 \text{ s}^{-1}\text{)}$,
- 9:00–10:00 → $0.9 \text{ (dm}^3 \text{ s}^{-1}\text{)}$,
- 10:00–11:00 → $0.4 \text{ (dm}^3 \text{ s}^{-1}\text{)}$,
- 11:00–12:00 → $0.1 \text{ (dm}^3 \text{ s}^{-1}\text{)}$.

Fig 6.12 presents windows of the editor allowing introduction of sanitary sewage inflow to the model.

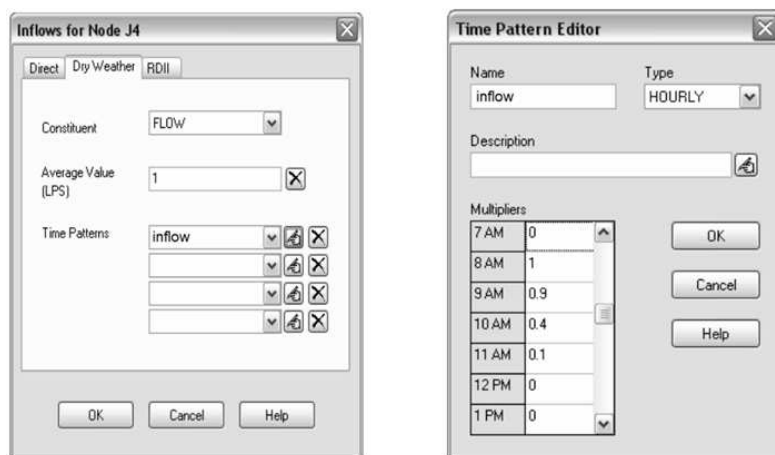


Fig. 6.12. Dry weather inflow for J4 and time pattern for dry weather

Next, to obtain the possibility of qualitative analyses in SWMM 5.0, it is required to define the pollutants available at tested watershed. Two types of the pollutants are accepted to further analyses – according to SWMM 5.0 documentation by Rossman (2010). The first one is Total Suspended Solids (TSS) (mg dm^{-3}), the second is Lead in ($\mu\text{g dm}^{-3}$). The Lead concentration was assumed as a fraction pollutant to TSS, making 25% of TSS concentration. Assignment of qualitative module and edition of pollutants is available in the main menu browser, in *Quality* → *Pollutants* where *Add object* should be selected. In a new edition window the name of the pollutant should be assigned i.e. TSS and then Lead. In case of the second pollutant the unit should be set as ($\mu\text{g dm}^{-3}$) and TSS should be assigned as *Co-fraction* with the value of 0.25. Fig. 6.13 presents the Pollutant Editor window for Lead.

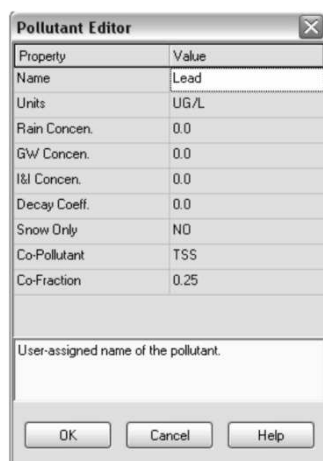


Fig. 6.13. Pollutant editor

The next step in qualitative modeling is to assign the type of development (residential, industrial, undeveloped) for area of subcatchments. The two types of development were assumed in our example, *Residential* and *Undeveloped* introduced to the model by selection of *Quality* → *Land uses* and *Add object*, the names of the development types should be input in *Land use name*. Then, we move forward to determine the type of function describing pollutants build up and washing off, separately for each pollutant tested. In the tab titled *Buildup* TSS should be selected from the *Pollutant* drop list (in our case Lead is a fraction of TSS so only definition of the second is required), then we select a POW type of function in *Function* menu item, note the appropriate units, mass per area and per time, for area set as *Normalizer*. The maximum buildup was assumed as 56 (kg ha^{-1}) with the rate of accumulation equal to 1.12 ($\text{kg ha}^{-1} \text{day}^{-1}$) so the above data are required to be assigned to *Max. buildup* and *Rate constant*. The *Power/ Sat. Constant* was assumed as 1.0. Next, we change the tab to *Washoff* and select the TSS from the list of available pollutants. The EMC (Event Mean Concentration) should be selected as a governing *Function* of Washoff load. The value of *Coefficient* should be assigned as 200 which reflects the mean concentration of TSS in mass per volume unit, in our example in mg L^{-1} , the zero value should be set in the remaining items. Fig. 6.14. present *Land Use Editor* for Buildup and Washoff for TSS and Residential areas.

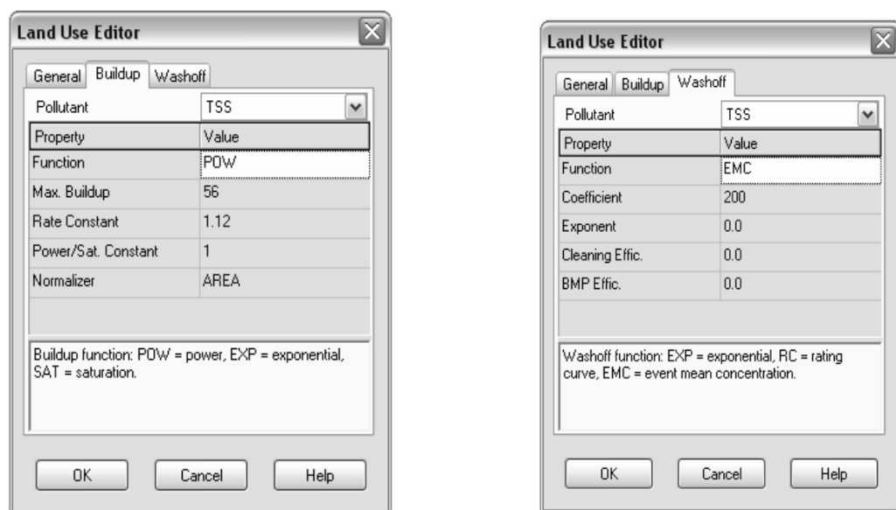


Fig. 6.14. Buildup Land Use Editor and Washoff Land Use Editor

Having finished the determination of Residential development we may continue to the Undeveloped areas. The name of the development, i.e. Undeveloped, should be assigned in the General tab into the item *Land use name*, then in Buildup tab the TSS should be selected from the list of the pollutants and POW ought to be

chosen as a governing function with the *Max buildup* equal to 28 (kg ha^{-1}) and *Rate constant* 0.56 ($\text{kg ha}^{-1} \text{ day}^{-1}$), area as *Normalizer* and *Power/Sat. Constant* equal to 1.0. The TSS again should be selected in the Washoff tab, EMC as a *Function* with the *Coefficeint* equal to 100, the remaining values should be assigned as 0. The next step in qualitative modeling in SWMM 5.0 is assignment of the individual type of development to the subcatchments, editing the properties of a basin and selecting the option *Land Uses*, then in the new window of *Land use assignment* it is required to precise the percentage share of each type of development on the area of watershed. For subcatments S1 and S2 these percentages are as follows: Residential =75%, Undeveloped=25% (see Fig. 6.15.), while for S3 it was assumed Residential =80%, Undeveloped=20%.

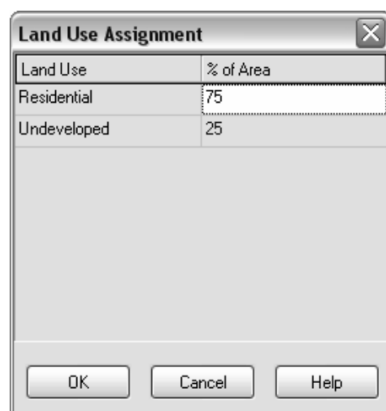


Fig. 6.15. Land Use Assignment for S1 and S2

The last stage of qualitative model development, for the presented example, is determination of the initial concentration of pollutants on the surface of subcatchments. Two manners are possible, by determination of the number of dry days before the modeled rainfall (*Antecedent dry days*) or by assignment the precise value of pollutants concentration in (kg ha^{-1}) as *Initial buildup* in the pollutants editor. In our case the first option was selected, *Antecedent dry days* number equal to 10 was assigned by *Option* → *Dates* → *Antecedent dry days*. Then, the qualitative analyses are available. Fig. 6.16. presents the time-varied concentrations of TSS in (mg dm^{-3}) for pipelines C1 and C4. TSS appears in the pipelines after the first hour of simulation duration, in the moment of rainfall event beginning. It is visible that occurrence of TSS may be observed earlier in the pipeline C1 than in C4, which is the clear result of distance between analyzed pipeline and subcatchment.

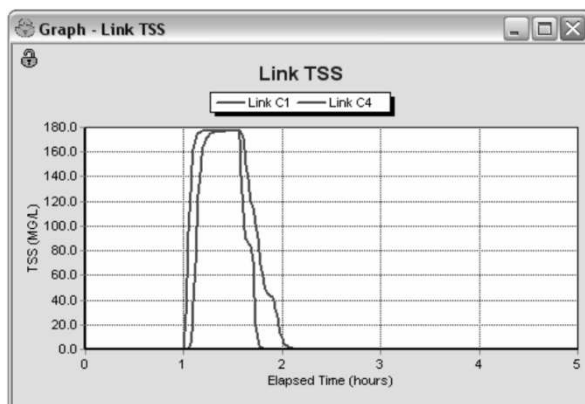


Fig. 6.16. Time dependant concentrations of TSS in pipelines C1 and C4

Fig. 6.17. shows the time-varying concentration of Lead in ($\mu\text{g dm}^{-3}$) in pipelines C1, C2 and C4. Again, similarly like in case presented in Fig. 6.16. pollutant appears in the pipelines at the beginning of rainfall event which caused flushing of the watershed surface and removal of the gathered sediments and their transport to the storm water system.

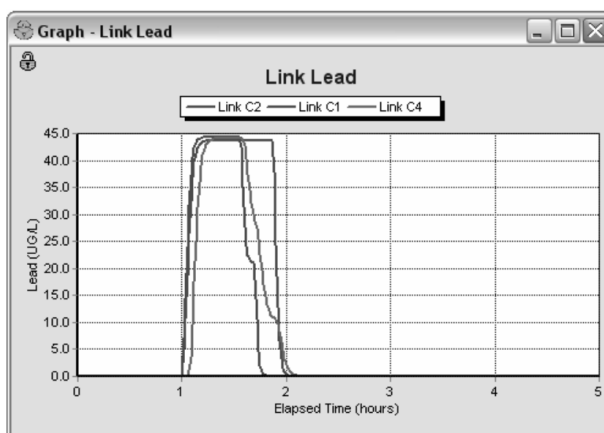


Fig. 6.17. Time-varying Lead concentration in C1, C2, C4 pipelines

6.4 Calibration file

The SMWMM 5.0 allows the comparison of modeled network functioning simulation results to the result of in situ measurements concluded in calibration file. Before application to the project the measurement data should be inputted in properly prepared text file. The calibration files contain the measurements results of the singular parameters which can be compared to the results of calculation in SWMM 5.0 and the validation may be presented in the graphical form as time-varying curves.

Calibration data may include:

- subcatchment runoff,
- subcatchment washoff,
- node water depth,
- link flow rate,
- node water quality,
- node lateral inflow,
- node flooding,
- groundwater flow,
- groundwater elevation,
- snow pack depth,
- link flow depth,
- link flow velocity.

To Upload the calibration file to the model in SWMM 5.0 it is necessary to use main menu option *Project* → *Calibration* data which triggers calibration file window presented in Fig. 6.18.

Calibration Variable	Name of Calibration File
Subcatchment Runoff	
Subcatchment Washoff	
Node Water Depth	
Link Flow Rate	
Node Water Quality	
Node Lateral Inflow	
Node Flooding	
Groundwater Flow	
Groundwater Elevation	
Snow Pack Depth	
Link Flow Depth	
Link Flow Velocity	

Buttons: Browse, Edit, OK, Cancel, Help

Fig. 6.18. Calibration data editor

The next step in uploading the necessary data is to select the proper position containing Calibration variable, than in the field *Name of calibration file* the assignment of path to file with *.dat extension concerning data is required, by direct typing or by using Browse option presented in Fig. 6.18.

The procedure for calibration file for another variable is the same as presented above. To edit the content of calibration file, the option *Edit*, when the file is selected, should be chosen. In case of a new file, after inputting its name with *.dat extension, clicking Edit allows to open the editor window and introduce data to the file. The New calibration file should be saved in the four columns format. The first column should contain the ID of a given object, the second – time duration of simulation in days, the third – time duration of simulation in hours and minutes or in numerical format, i.e. 5:12 and 5.2 (introducing 0 means the beginning of the simulation), the fourth, last column ought to contain the numerical value of tested parameters. The exemplary calibration file for our simplified model is presented below.

```
J5
0 1:10 0.2
0 1:20 0.5
0 1:30 0.51
0 2:00 0.63
0 2:30 0.56
```

The above text file presents storm water depth for node J5 in the given period of time since the beginning of simulation, for the first day of calculations. The first row of the table shows that at time of 1 hour and 10 minutes storm water depth is at height of 0.2 m. The remaining rows should be understood analogically. Fig. 6.19 presents the calculated by SWMM 5.0 (red line) and measured and included in calibration file (green points) depths of waste water in node J5.

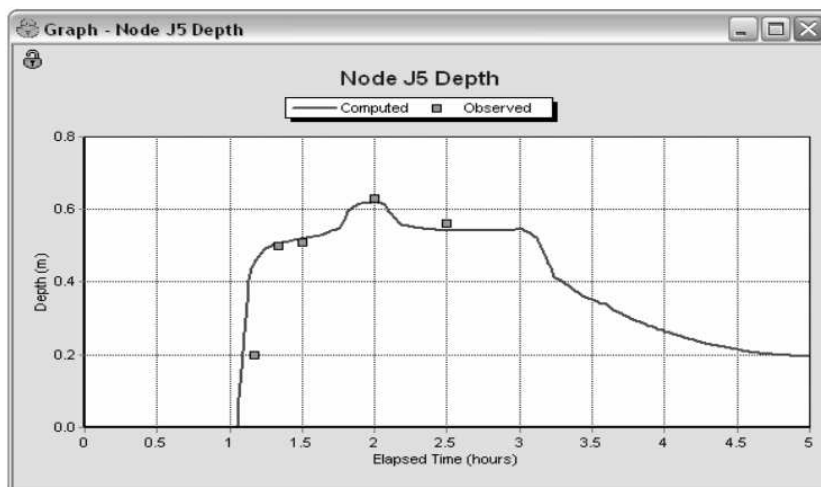


Fig. 6.19. Comparison of calculated by SWMM 5.0 and measured depths of waste water in node J5

7 Exemplary calculations of hydraulics and pollutants transport in real sewer systems by SWMM 5.0

7.1 *Simulation of hydraulics and pollutants transport in real storm water system*

This chapter contains the exemplary quantitative and qualitative numerical simulation of the real storm water system located in the residential district in a town of population equal to approx. 65 000. The example presented below shows each required step of model development, setting the model parameters, running the calculations and, finally, analysis of the results.

7.1.1 Data for simulations

The task is to perform numerical calculations of quantitative and qualitative operational conditions of the selected part of storm water system for the rainfall event presented below in Table 7.1. We assume the time duration of simulation equal to 24 hours. The presented exercise is based on data used also at the scientific paper published in Ecological Chemistry and Engineering A (Widomski *et. al.*, 2012).

Table 7.1. Time dependant characteristics of assumed rainfall event

Day	Time	Rain volume	Day	Time	Rain volume
(month/day/year)	(hr:min)	(mm)	(month/day/year)	(hr:min)	(mm)
03/16/2010	00:00	0	03/16/2010	09:00	0
03/16/2010	01:00	0	03/16/2010	10:00	0
03/16/2010	02:00	0	03/16/2010	11:00	0
03/16/2010	03:00	0	03/16/2010	12:00	0
03/16/2010	04:00	0	03/16/2010	13:00	0
03/16/2010	05:00	0	03/16/2010	14:00	0
03/16/2010	06:15	5.7	03/16/2010	15:00	0
03/16/2010	06:30	5.2	03/16/2010	16:00	0
03/16/2010	06:45	8.1	03/16/2010	17:00	0
03/16/2010	07:00	7.4	03/16/2010	18:00	0
03/16/2010	07:15	10.2	03/16/2010	19:00	0
03/16/2010	07:30	9.7	03/16/2010	20:00	0
03/16/2010	07:45	8.6	03/16/2010	21:00	0
03/16/2010	08:00	9.1	03/16/2010	22:00	0
03/16/2010	08:15	9.6	03/16/2010	23:00	0
03/16/2010	08:30	6.7			
03/16/2010	08:45	4.3			

General input data:

Characteristics of storm water system (diameters, lengths and elevations) – read from the map.

Material – concrete.

Area of subcatchments – read from the map. The digital map (bmp, emf, wmf, jpg and jpeg files are acceptable) of the considered watershed was used in model development.

Type of wave – dynamic.

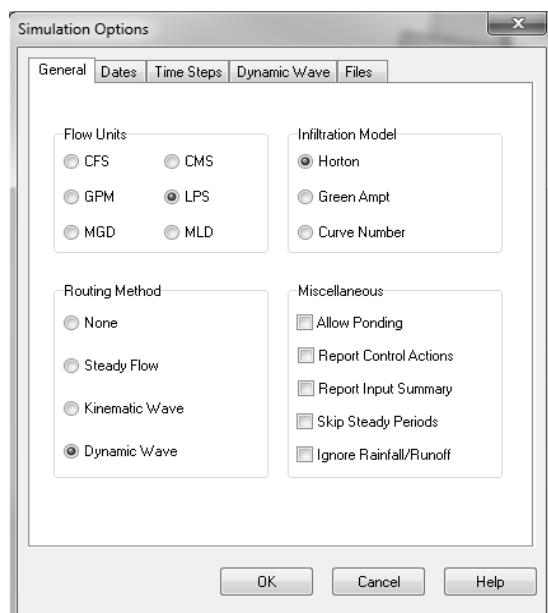
Input data for qualitative modelling – Table 7.2., we assume two types of basins – residential area and undeveloped area.

Table 7.2. Models and input data applied to qualitative calculations

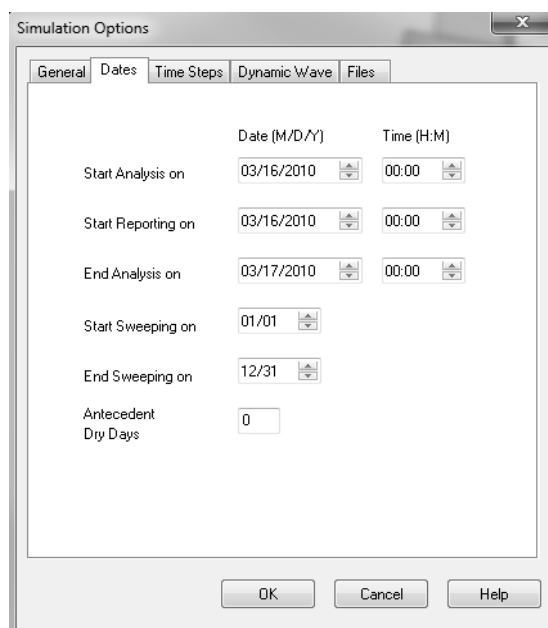
		Pollutant buildup		Pollutant washoff	
Model		$B = C_1(1 - e^{C_2 t})$ B – pollutant buildup (mg dm^{-3}) C_1 – maximum buildup possible (mg dm^{-3}) C_2 – buildup rate constant (d^{-1}) t – time (d)		$W = C_3 \cdot Q^{C_4}$ W – concentration of pollutant in surface runoff C_3 – washoff coefficient, equal to EMC (-) C_4 – exponent, $C_4=1$ (-) Q_s – surface runoff flow rate ($\text{dm}^3 \cdot \text{s}^{-1}$)	
Applied values	Residential area	TSS	$C_1=50$ (mg dm^{-3}) $C_2=2$ (d)	TSS	$EMC=101$ (-)
		TP	Co-pollutant to TSS 58 mg TP per kg TSS	TP	$EMC=0.34$ (-)
		TN	Co-pollutant to TSS 550 mg TN per kg TSS	TN	$EMC=2.64$ (-)
	Undeveloped area	TSS	$C_1=100$ (mg dm^{-3}) $C_2=3$ (d)	TSS	$EMC=70$ (-)
		TP	Co-pollutant to TSS 49 mg TP per kg TSS	TP	$EMC=0.12$ (-)
		TN	Co-pollutant to TSS 460 mg TN per kg TSS	TN	$EMC=1.51$ (-)

7.1.2 Solution

1. First, we need to set the main, general options of our simulation. Go to *Data – Options*, open *Simulation Options* and select *General*. Now you can set the most fundamental options of simulation – units, type of routing method etc.

Fig. 7.1. *General* options of simulation

2. Then, you can enter *Dates* and set the period of simulations.

Fig. 7.2. *Temporal* parameters of simulation

3. Next, select *Time Steps* and correct time step settings. Set time step equal to 5 s.

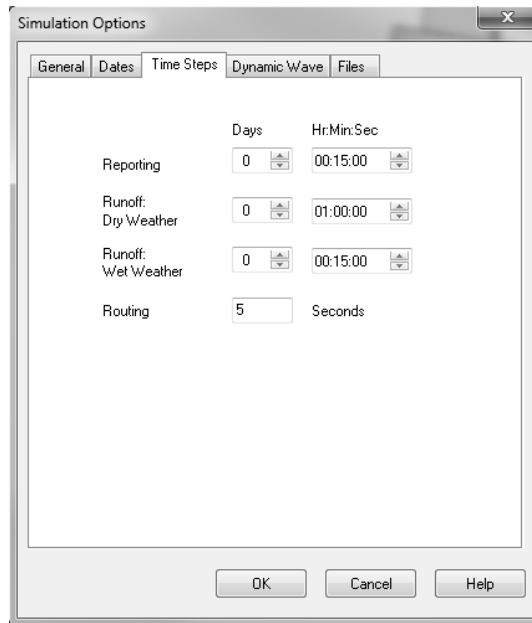


Fig. 7.3. *Time Steps* setting

4. Go to *Dynamic Wave* and adjust the available settings.

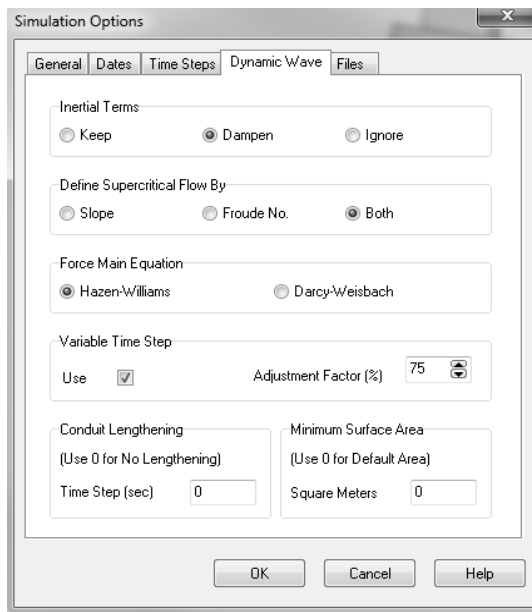


Fig. 7.4. *Dynamic Wave* settings

5. After completing the *Options* setting we need to create the input data for the modelled rainfall event. Select *Hydrology – Rain Gages* and using a + sign create a new *Rain Gage*. Then input the data presented in Tab. 7.1. Remember to change the *Rain Format* to *Volume* and *Rain Units* to (mm).

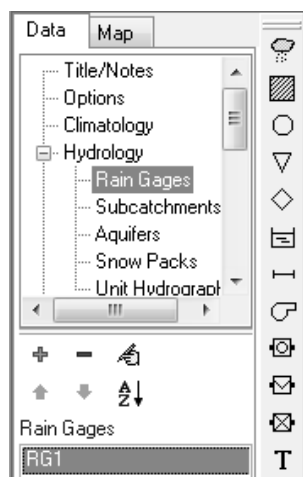
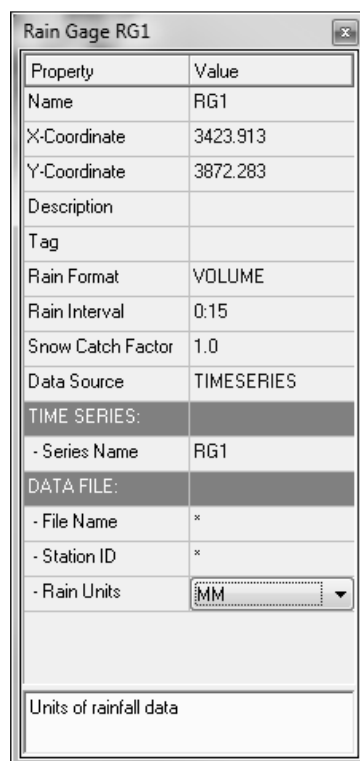


Fig. 7.5. Creating the new *Rain Gage*

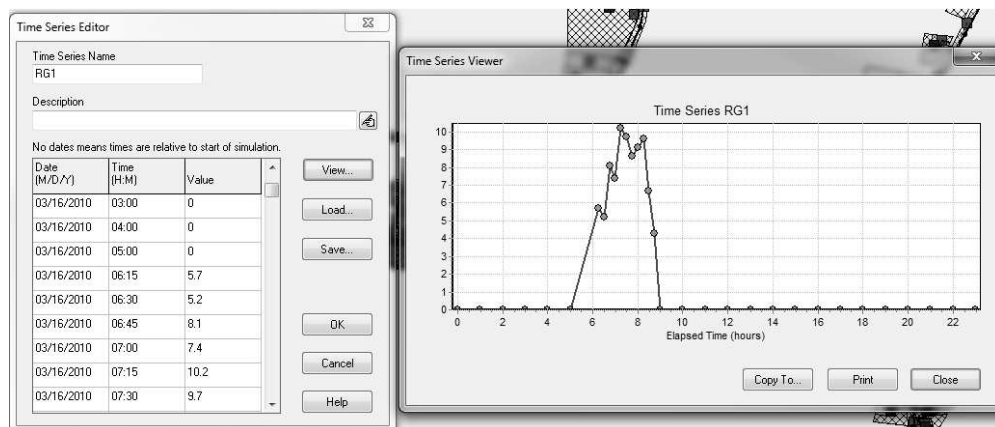
Property	Value
Name	RG1
X-Coordinate	3423.913
Y-Coordinate	3872.283
Description	
Tag	
Rain Format	VOLUME
Rain Interval	INTENSITY
Snow Catch Factor	VOLUME
	CUMULATIVE
Data Source	TIMESERIES
TIME SERIES:	
- Series Name	RG1
DATA FILE:	
- File Name	*
- Station ID	*
- Rain Units	IN
Type of rainfall data recorded at rain gage	

Fig. 7.6. Changing the *Rain Format*



Rain Gage RG1

Property	Value
Name	RG1
X-Coordinate	3423.913
Y-Coordinate	3872.283
Description	
Tag	
Rain Format	VOLUME
Rain Interval	0:15
Snow Catch Factor	1.0
Data Source	TIMESERIES
TIME SERIES:	
- Series Name	RG1
DATA FILE:	
- File Name	*
- Station ID	*
- Rain Units	MM
Units of rainfall data	

Fig. 7.7. Adjusted *Rain Units* to mmFig. 7.8. Completed *Rain Gage* for our simulation

- Now we are ready to start building our model. Upload the map of modelled basin by *View – Backdrop – Load*.

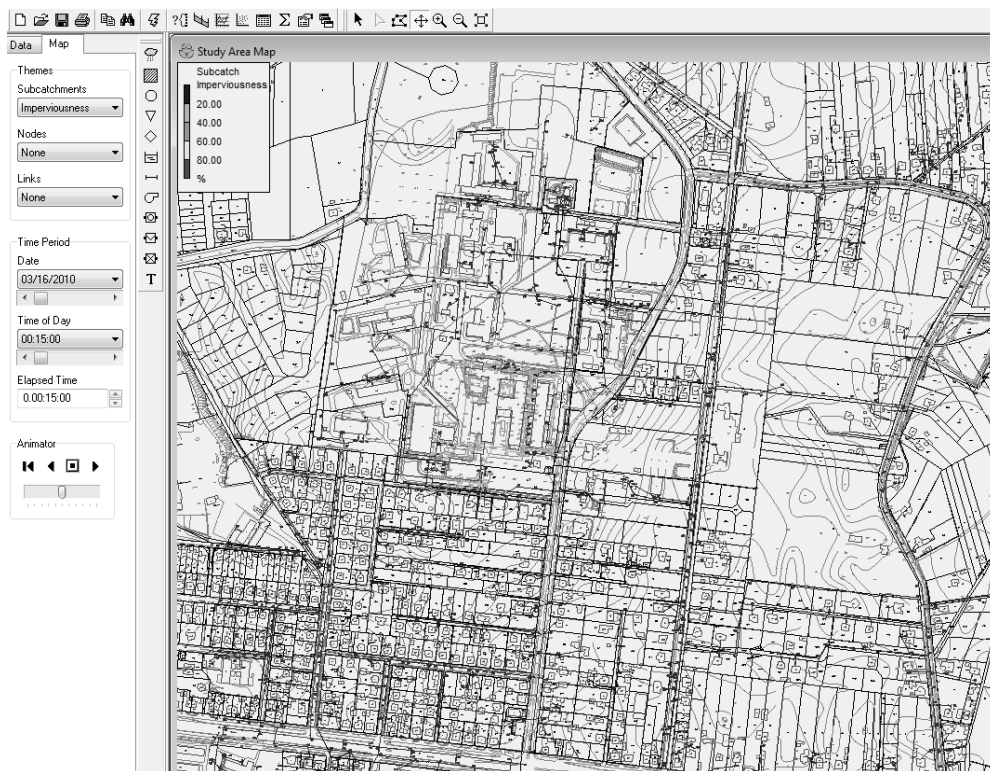


Fig. 7.9. Map of the study area – storm water system

7. Now we start to draw the storm water system starting from marking the nodes in locations of chambers. Input all the necessary data of each chamber (most crucial are elevation and depth, read from the map) to node characteristics.



Fig. 7.10. Nodes and node parameters

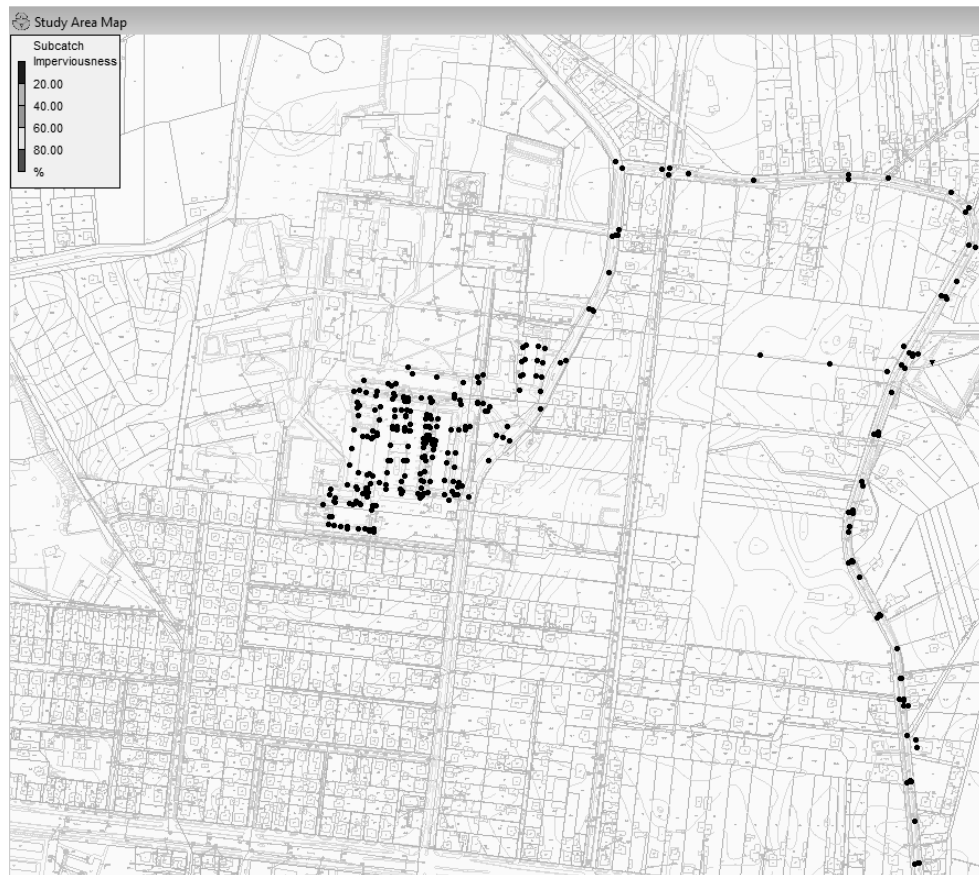


Fig. 7.11. Developed network of nodes

- Set the Free outfall in the location of outflow from the modelled network – outflow elevation and type (*FREE*) are necessary.

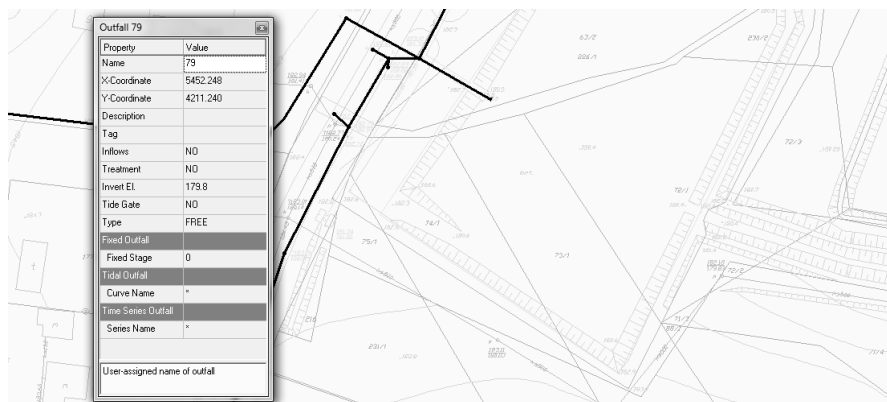


Fig. 7.12. Model outflow

9. Then, join the nodes (chambers) and outflow by links representing pipes, inputting all the geometrical and material characteristics of the real pipelines. To each link the following info is required: shape, maximum depth (diameter), length, roughness and inlet and outlet node.

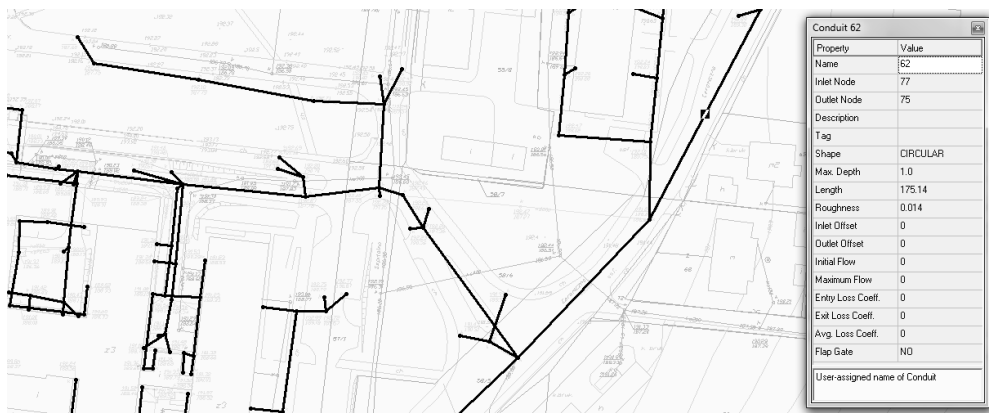


Fig. 7.13. Drawing the links representing pipelines

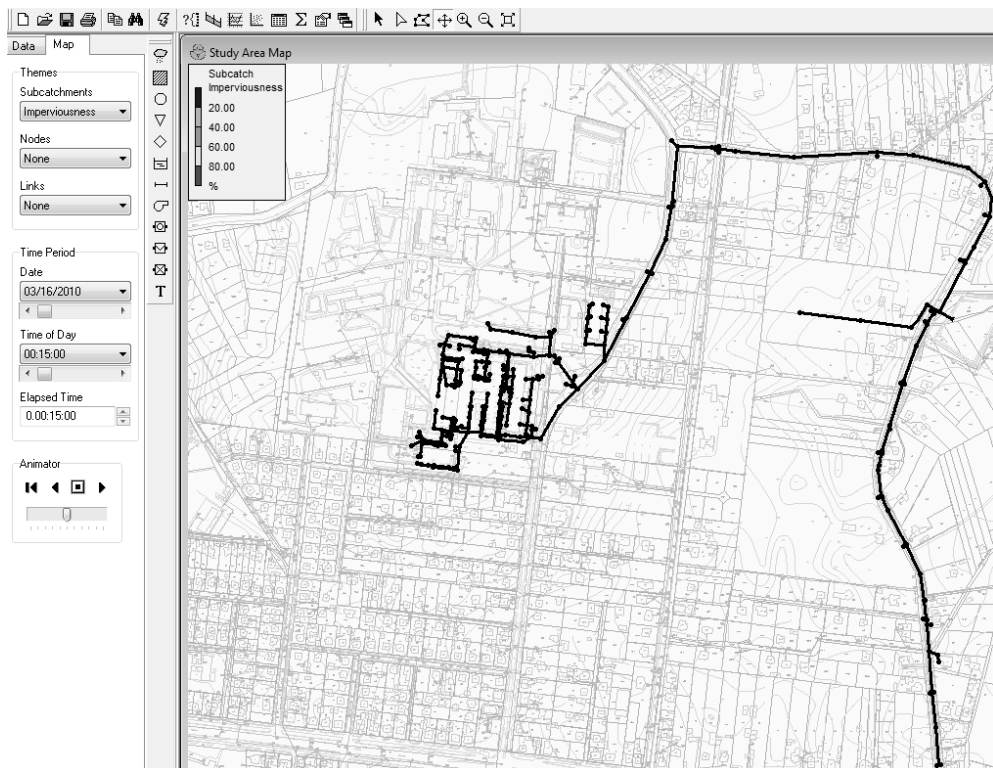


Fig. 7.14. The developed model consisting of nodes and links

10. Now we need to draw the subcatchments on each drained area – using the button Subcatchment. Then, carefully input all the required data and set the out-flowing node for each subcatchment. The most crucial characteristics of the subcatchment are: Rain Gage, Outlet (the draining node), area, width, inclination in %, percent of impervious area, Manning roughness for impervious and pervious area and land use type (available after setting quality parameters).



Fig. 7.15. The designed subcatchments



Fig. 7.16. Subcatchments characteristics

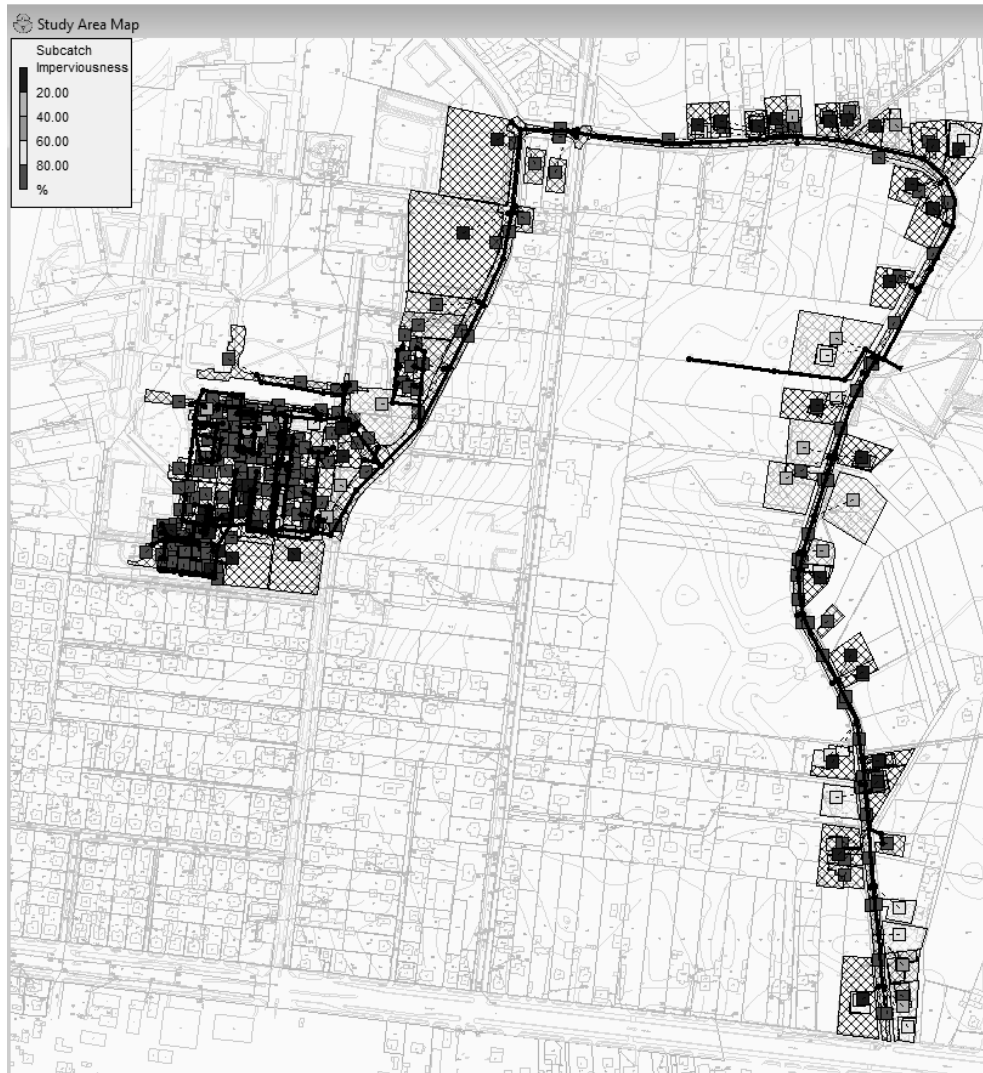


Fig. 7.17. The developed model of storm water pipelines with subcatchments

11. We have just finished the hydraulic model of our storm water network, now we should start the quality modelling. We need to create the three pollutants: TSS, TN and TP (Total Suspended Solids, Total Nitrogen, Total Phosphorus). Go to Quality – Pollutants and press the green +, then set the data according to Tab. 4.2.

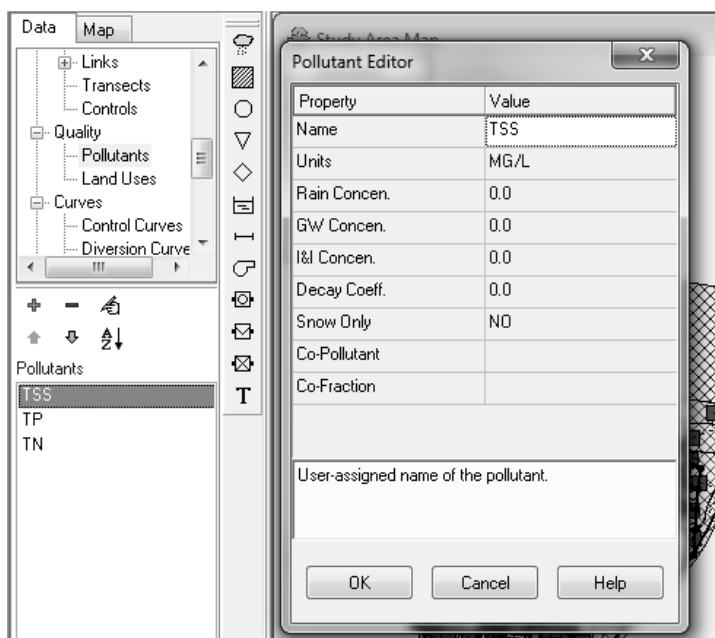


Fig. 7.18. Pollutant TSS

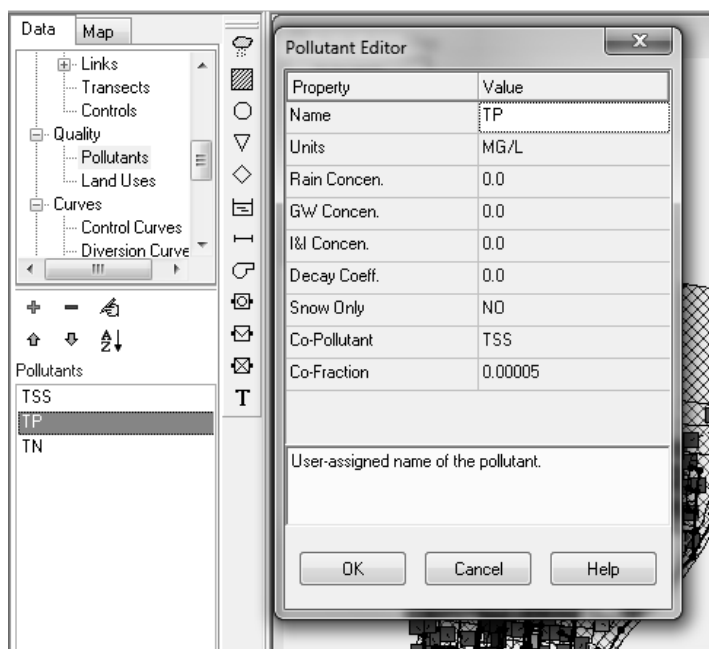


Fig. 7.19. Pollutant TP as co-fraction of TSS

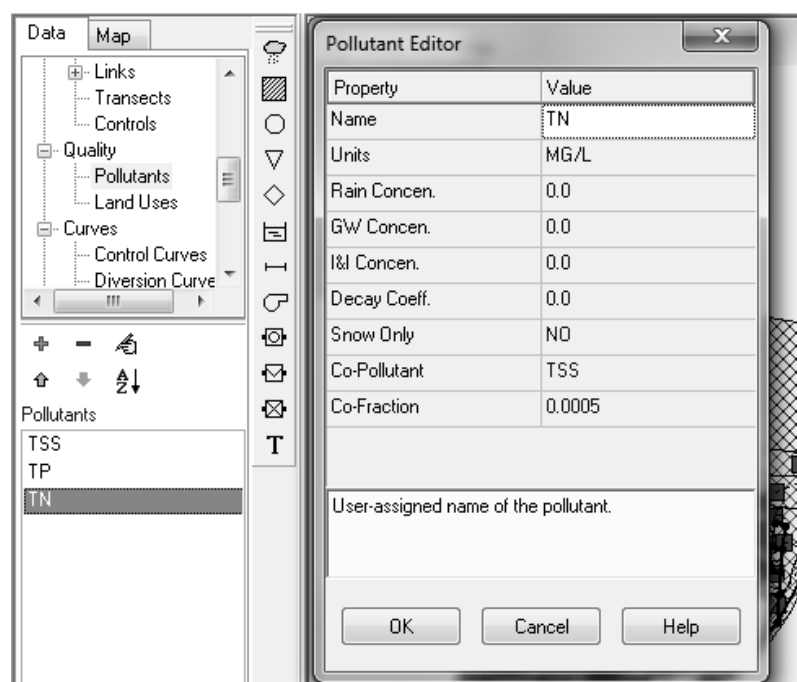


Fig. 7.20. Pollutant TN as co-fraction of TSS

12. Now we need to create and edit two types of land use – Residential and Undeveloped.

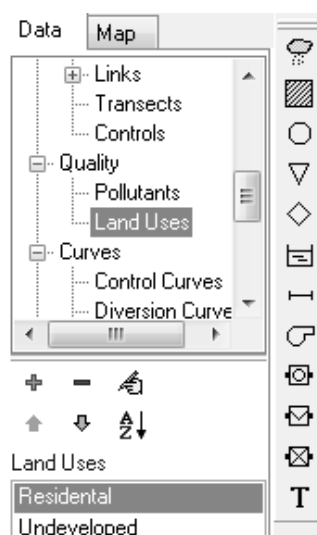


Fig. 7.21. Created land uses

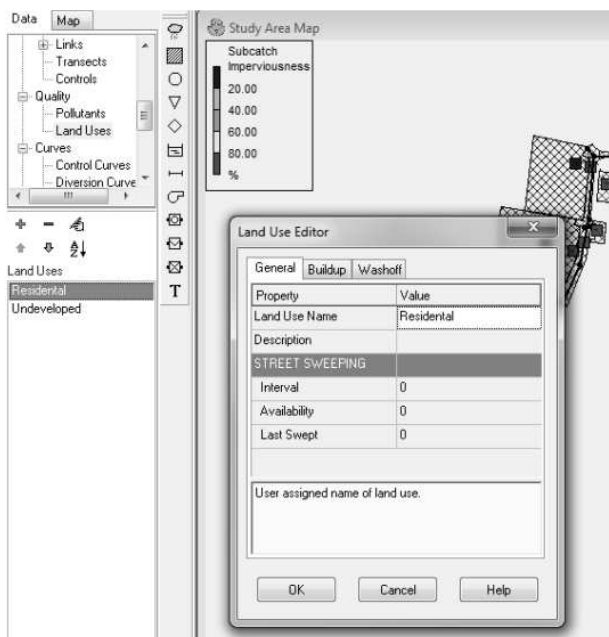


Fig. 7.22. Land use editor and two land uses created

13. Now we need to input the data for pollutants *Buildup* and *Washoff* from Table 7.2. for the both previously created land uses.

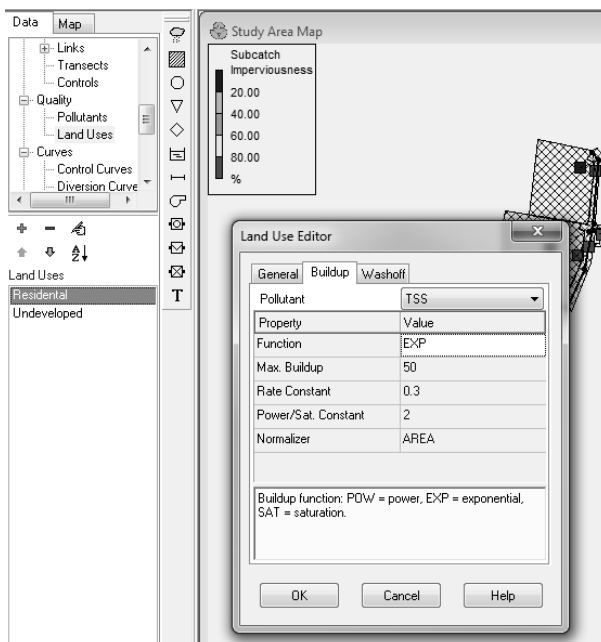


Fig. 7.23. TSS build-up data for Residential land use

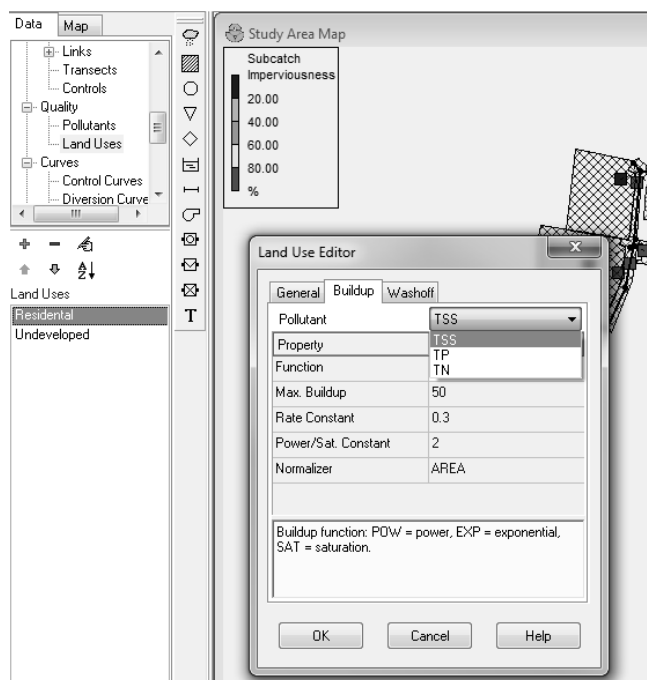


Fig. 7.24. *Buildup* data for Residential land use – selection of pollutant

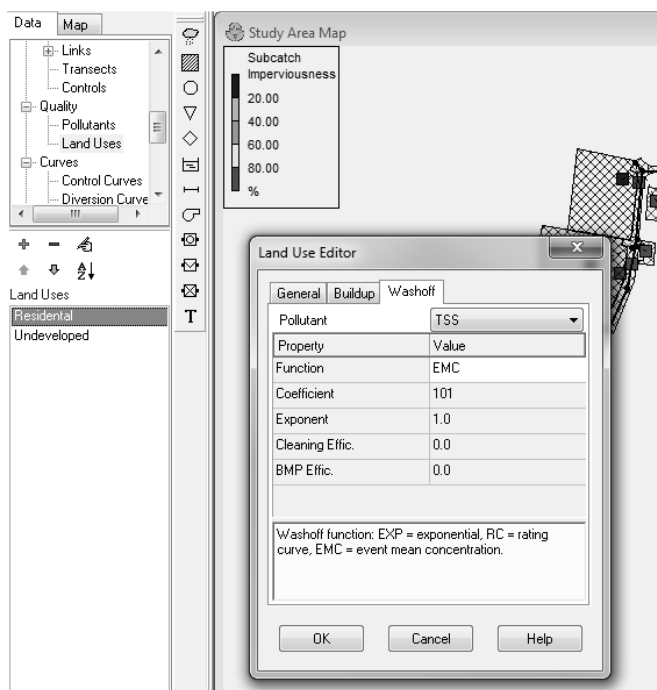


Fig. 7.25. *Washoff* parameters for TSS and Residential land use

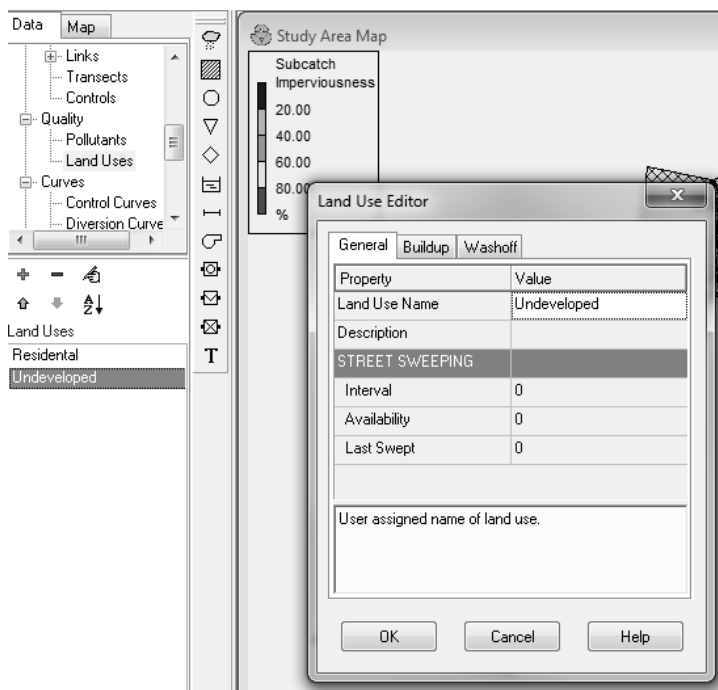


Fig. 7.26. Undeveloped land use general data

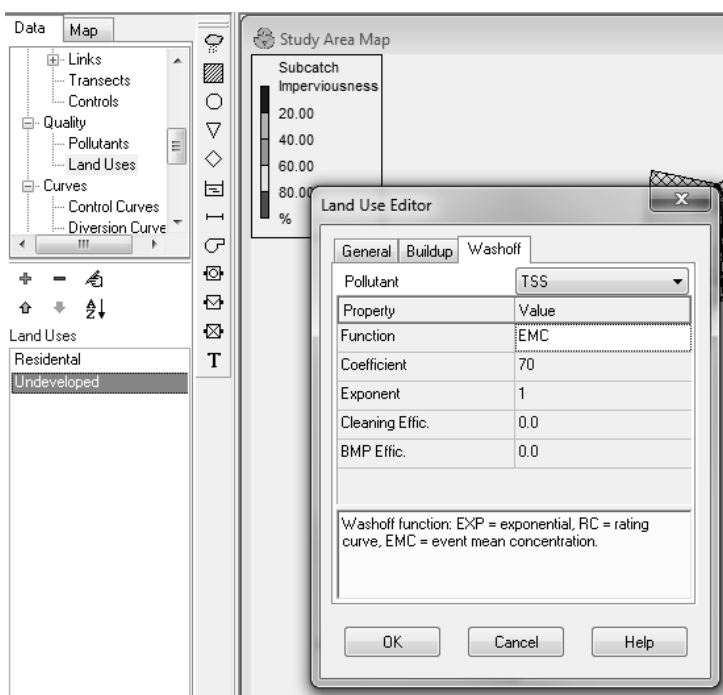


Fig. 7.27. Washoff parameters for TSS and Undeveloped land use

14. Now we need to carefully assign land use type to each subcatchment.

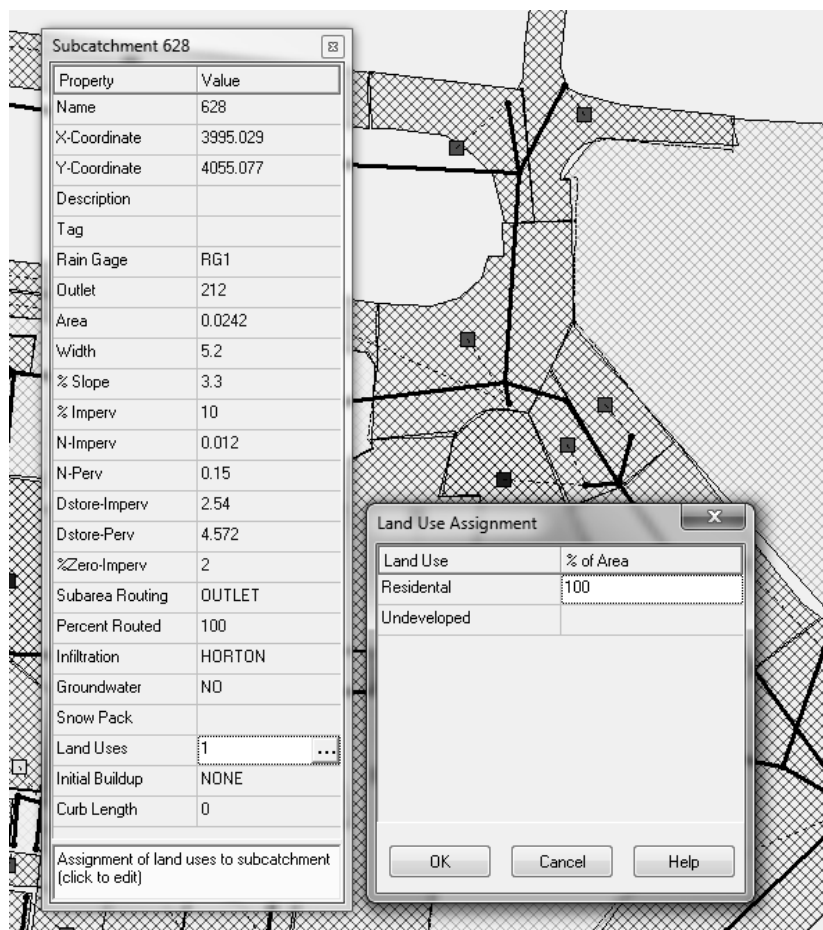


Fig. 7.28. Land use assignment

15. When we are done, our quantitative and qualitative model is ready. Press yellow lighting icon or select *Project – Run Simulation*. Then check the values of all errors displayed which should be, for a successful simulation, lower than 3% (see figure 7.29).
16. Having run the simulation we may study the results of calculations. First, let's check the hydraulic conditions (i.e. flow velocity and flooding) during the time of the highest storm water flow (07:30). To obtain the required results it is required to scroll down the lists available under Subcatchments, Nodes and Links and set the proper time duration of simulation.

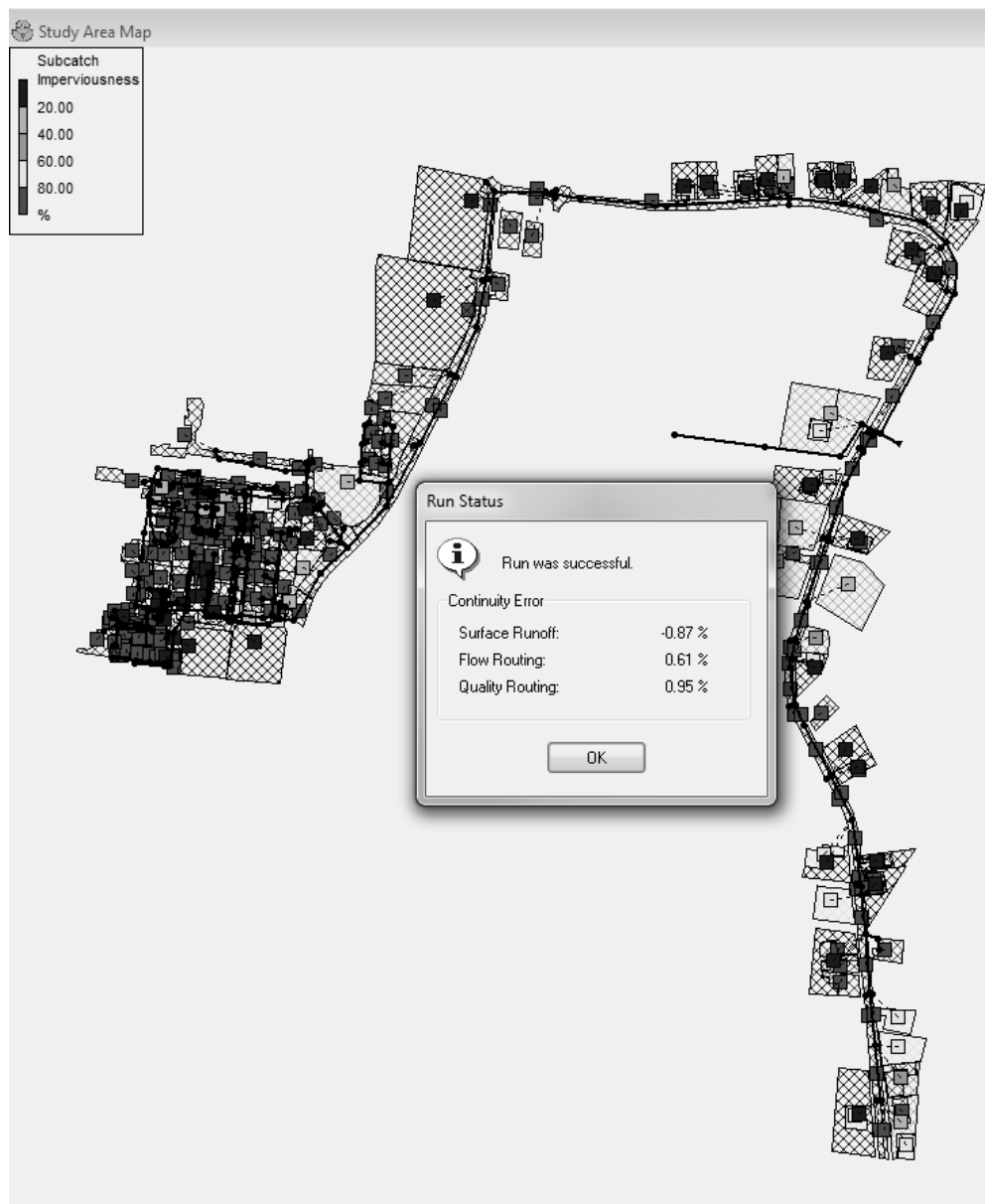


Fig. 7.29. Simulation after run, all errors are acceptable

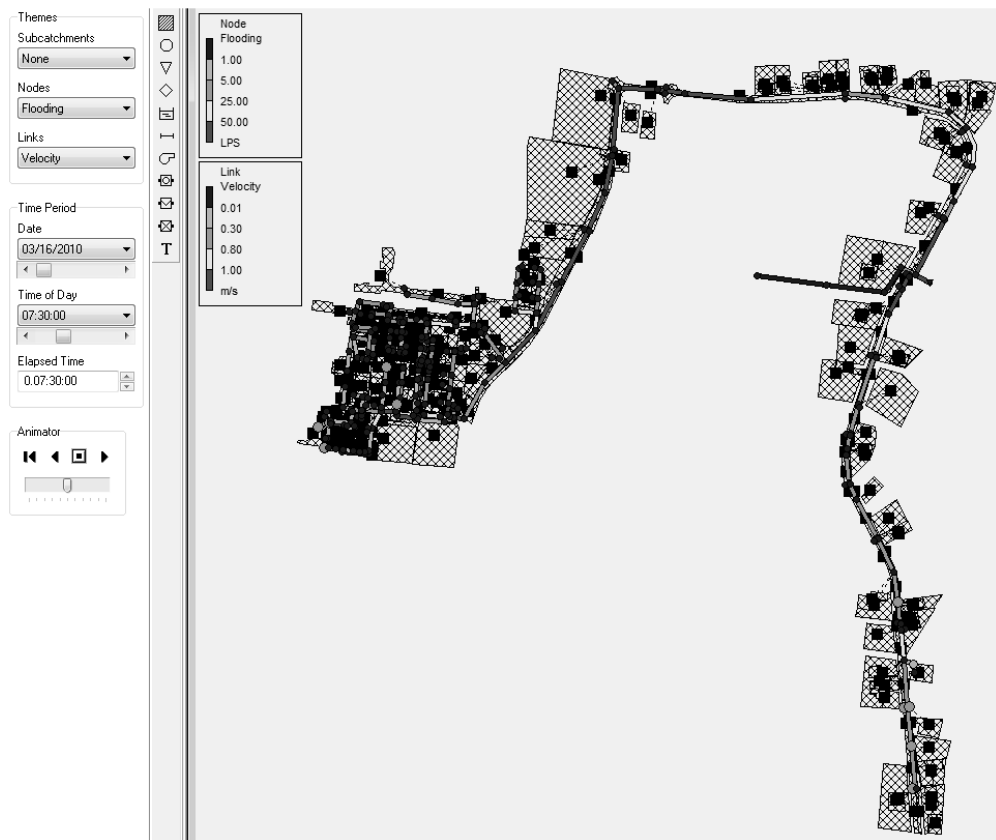


Fig. 7.30. Results of hydraulic model - velocity of flow and flooding

17. Now we can draw the profile of selected part of our network – we are going to select the pipeline located in the right bottom part of the model, where flooding was observed.

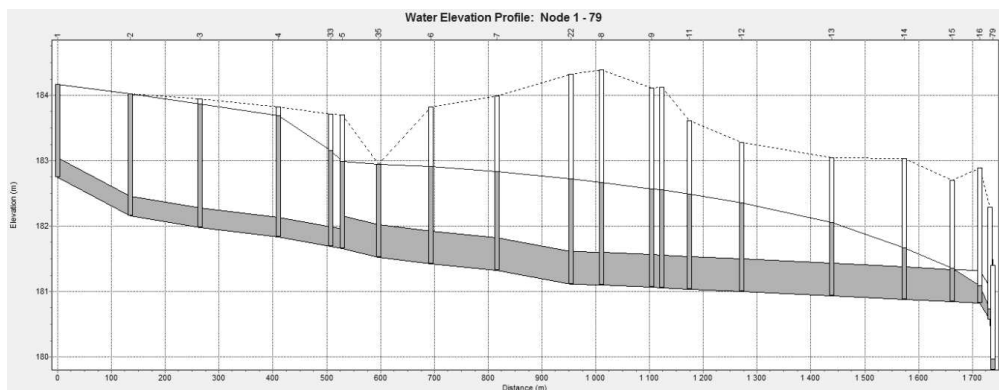


Fig. 7.31. Profile of the selected pipeline presenting modeled flooding

18. Finally, we can check the results of numerical calculations of storm water quality by selecting TSS in Links menu.

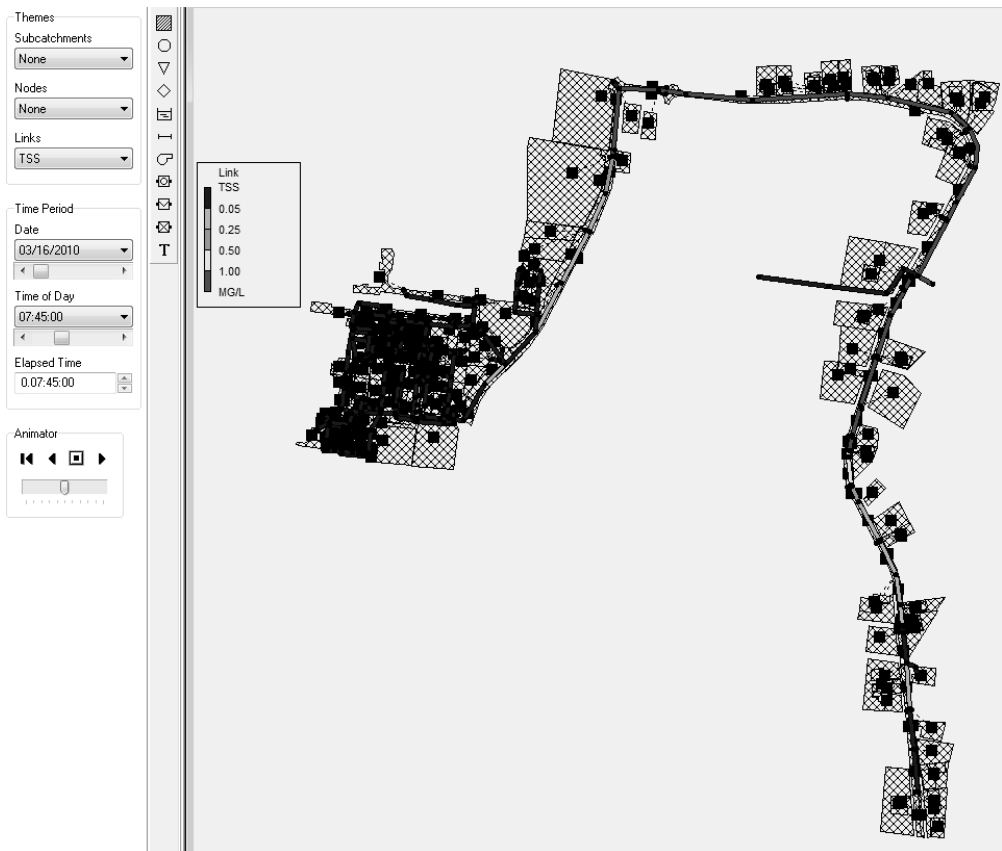


Fig. 7.32. TSS concentration distribution in modelled network

The further usage of the presented model is limited by lacking model calibration, requiring the application of in situ measurements results into the calibration file. The positively calibrated and validated model of the real, existing sewer system may be successfully used in network management.

8 Bibliography

1. Abdul-Talib S., Ujang Z., Vollertsen J., Hvitved-Jacobsen T.: Sewer networks as bio-reactors – extending the transport function of sewers. Conference on Water and Drainage, Kuala Lumpur, Malaysia, 2003.
2. Ackers J.C., Butler D., May R.W.P.: Design of sewers to control sediment problems. Construction Industry Research and Information Association, Report 141, London 1996.
3. Andoh R.Y.G., Smisson R.P.M.: The practical use of wastewater characterization in design. *Water Science and Technology*, 33(9), 127-134, 1996.
4. Angelakis A.N., Koutsoyiannis D., Tchobanoglous G.: Urban wastewater and stormwater technologies in ancient Greece. *Water Research*, 39(1), 210-220, 2005.
5. Arthur S., Ashley R.M.: Near bed solids transport rate prediction in a combined sewer network. *Water Science and Technology*, 36(8-9), 129-134, 1997.
6. Ashley R.M., Hvitved-Jacobsen T., Bertrand-Krajewski J.-L.: Quo vadis sewer process modeling? *Water Science and Technology*, 39(9), 9-22, 1999.
7. ATV-DVWK – A110P: Wytyczne do hydraulicznego wymiarowania i sprawdzania przepustowości kanałów i przewodów ściekowych. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., GFA, Seidel-Przywecki, Warszawa 1988.
8. Bąk Ł., Górski J., Górka K., Szela B.: Zawartość zawiesin i metali ciężkich w wybranych falach ścieków deszczowych w zlewni miejskiej. *Ochrona Środowiska*, 32(2), 49-52, 2012.
9. Berlamont J.E., Torfs H.M.: Modeling (partly) cohesive sediment transport in sewer systems. *Water Science and Technology*, 33(9), 171-178, 1996.
10. Błaszczyk W.: Projektowanie sieci kanalizacyjnych, Wydanie III. Arkady, Warszawa 1965.
11. Błaszczyk W., Stomatello H., Błaszczyk P.: Kanalizacja. Sieci i pompownie. Arkady, Warszawa 1983.
12. Butler D., Friedler E., Gatt K.: Characterising the quantity and quality of domestic wastewater inflows. *Water Science and Technology*, 31(7), 13-24, 1995.
13. Bylka J.: Kalibracja, weryfikacja i walidacja jako narzędzia oceny użyteczności modelu układu transportującego wodę. Konferencja naukowo-techniczna GIS, modelowanie i monitoring w zarządzaniu systemami wodociągowymi i kanalizacyjnymi. Warszawa 2013.
14. Crabtree R.W.: A classification of combined sewer sediment types and characteristic. WRc report No. ER 324 E, 1988.

15. Crabtree R.W., Ashley R., Gent R.: Mousetrap: Modelling of real sewer sediment characteristics and attached pollutants. *Water Science and Technology*, 31(7), 43-50, 1995.
16. Dąbrowski W.: Oddziaływanie sieci kanalizacyjnych na środowisko. Wydawnictwo Politechniki Krakowskiej, Kraków 2004.
17. Denczew S.: Podstawy modelowania systemów eksploatacji wodociągów i kanalizacji. Monografie Komitetu Inżynierii Środowiska PAN, 37, 2006.
18. Edel R.: Odwodnienie dróg. WKŁ, Warszawa 2006.
19. Even S., Poulin M., Mouchel J., Seidl M., Servais P.: Modelling oxygen deficits in the Seine River downstream of combined sewer overflows. *Ecological Modelling*, 173, 177-196, 2004.
20. Gałabuda G.: Określenie taryf a opłaty za ścieki opadowe. *Wodociągi i Kanalizacja*, 4(50), 36-37, 2008.
21. Garsdal H., Mark O., Dorge J.: Mousetrap: Modelling of water quality processes and the interaction of sediments and Pollutants in sewers. *Water Science and Technology*, 31(7), 33-41, 1995.
22. Green M., Shelef G., Messing A.: Using the sewerage system main conduits for biological treatment – Greater Tel-Aviv as a conceptual model. *Water Research*, 19(8), 1023-1028, 1985.
23. Heidrich Z.: Kanalizacja. Wydawnictwo Szkolne i Pedagogiczne, Wydanie I, Warszawa 1999.
24. Huisman J.L., Burckhardt S., Larsen T., Krebs P., Gujer W.: Propagation of waves and dissolved compounds in a sewer. *Journal of Environmental Engineering ASCE*, 128(1), 12-20, 2000.
25. Huisman J. L.: Transport and transformation process in combined sewers. *IHW Schriftenreihe*, 10, 1-180, 2001.
26. Hvitved-Jacobsen T.: SEWER PROCESSES Microbial and Chemical Process Engineering of Sewer Networks. CRC PRESS, Boca Raton, London, New York, Washington 2002.
27. Hvitved-Jacobsen T., Vollertsen J., Tanaka N.: Wastewater quality changes during transport in sewers – an integrated aerobic and anaerobic model concept for carbon and sulfur microbial transformations. *Water Science and Technology*, 38(10), 257-264, 1998.
28. Imhoff K., Imhoff K.R.: Kanalizacja miast i oczyszczanie ścieków. Projprzem-EKO, Bydgoszcz 1996.
29. James A. red. Ang. Kempa E.S. red. Pl.: Modelowanie matematyczne w oczyszczaniu ścieków i ochronie wód. Arkady, Warszawa 1986.
30. Jeżowiecka-Kabsch K. Szewczyk H.: Mechanika Płynów. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2001.

31. Jilati A., Widomski M., Łagód G.: Influence of conduit geometrical characteristics on sewage flow parameters. *Proceedings of ECOpole*, 2(2), 329-335, 2008.
32. Karpiuk R., Jarosławski W.: Modelowanie funkcjonowania wybranej sieci kanalizacji deszczowej przy wykorzystaniu programu EPA SWMM 5. Praca Magisterska pod kierunkiem dr inż. Kowalskiej B., Zakład Wodociągów i Kanalizacji, Lublin 2007.
33. Kashefipour S.M., Falconer R.A.: Longitudinal dispersion coefficient in natural channels. *Water Research*, 36, 1596-1608, 2002.
34. Klepacka B., Dolecka J., Dolecki J., Usakiewicz A.: Wodociągi i kanalizacja, część 2 kanalizacja – Materiały pomocnicze do ćwiczeń projektowych. Politechnika Białostocka, Białystok 1999.
35. Klimiuk E., Łebkowska M.: Biotechnologia w ochronie środowiska. PWN, Warszawa 2005.
36. Koch C.M., Zandi I.: Use of pipelines as aerobic biological reactors. *Journal Water Pollution Control Federation*, 45(12), 2537-2548, 1973.
37. Kotowski A.: Podstawy bezpiecznego wymiarowania odwodnień terenów. Seidel-Przywecki, Warszawa 2011.
38. Krajewski P., Niedzielski W.: Sieci kanalizacyjne jako układu transportu i podczyszczania ścieków – część I. *Forum eksploatatora*, 19(2), 40-44, 2005.
39. Krajewski P., Niedzielski W.: Sieci kanalizacyjne jako układu transportu i podczyszczania ścieków – część II. *Forum eksploatatora*, 20(3), 36-40, 2005a.
40. Królikowska J., Królikowski A.: Wody opadowe. Odprowadzanie, zagospodarowanie, podczyszczanie i wykorzystanie. Seidel-Przywecki, 2012.
41. Krukowski M.: Porównanie wartości współczynników dyspersji zanieczyszczeń pasywnych wyznaczonych z pomiarów na rzece Wkrze z obliczonymi zależnościami empirycznymi. *Przegląd Naukowy Inżynieria i Kształtowanie Środowiska*, 1(24), 228-239, 2002.
42. Krupa K.: Modelowanie, symulacja i prognozowanie: systemy ciągłe. WNT, Warszawa 2008
43. Kwietniewski M.: GIS w wodociągach i kanalizacji. PWN, Warszawa 2008.
44. Kwietniewski M., Gębski W., Wronowski N.: Monitorowanie sieci wodociągowych i kanalizacyjnych. Polskie Zrzeszenie Inżynierów i Techników Sanitarnych, Warszawa 2005.
45. Leśniewski M.: Wdrażanie hydrodynamicznego modelu sieci kanalizacyjnej Warszawy. *Instal*, 279, 56-59, 2008.
46. Licznar P.: Współczesna techniki gromadzenia danych opadowych dla modeli hydrodynamicznych sieci kanalizacyjnej. *Instal*, 279, 64-68, 2008.
47. Łagód G., Widomski M., Suchorab Z., Wróbel K.: Modelowanie transportu i biodegradacji zanieczyszczeń w systemach kanalizacyjnych. red. L. Pawłowski, Monografie Komitetu Inżynierii Środowiska PAN, 72, 2010.

48. Łagód G., Sobczuk H., Suchorab Z., Widomski M.: Advection-dispersion pollutant and dissolved oxygen transport as a part of sewage biodegradation model. *Environment Protection Engineering*, 35(3), 305-317, 2009.
49. May R.W.P., Ackers J.C., Butler D., John S.: Development of design methodology for self-cleansing sewers. *Water Science and Technology*, 33(9), 195-205, 1996.
50. McGregor I., Ashley R.M., Oduyemi K.O.K.: Pollutant release from sediments in sewer systems and their potential for release into receiving waters. *Water Science and Technology*, 28(8-9), 161-169, 1993.
51. Mehrer H., Stolwijk N.A.: Heroes and highlights in the history of diffusion. *Diffusion Fundamentals*, 11(1), 1-32, 2009.
52. Mitosek M.: Mechanika płynów w inżynierii środowiska. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 1997.
53. MOUSE PIPE FLOW – Reference Manual. DHI Water & Environment, Hørsholm 2003.
54. Myszograj S.: Kolektory ściekowe jako bioreaktor. w: II Kongres Inżynierii Środowiska, materiały, tom 1, Monografie Komitetu Inżynierii Środowiska PAN, 32, 865-872, 2005.
55. Myszograj S.: Zmiany składu ścieków w czasie transportu siecią kanalizacyjną. *Gaz, woda i technika sanitarna*, 7-8, 10-14, 2006.
56. Nalluri C., Alvarez E.M.: The influence of cohesion on sediment behavior. *Water Science and Technology*, 25(8), 151-164, 1992.
57. Nalluri C., Ghani A.A.: Design options for self-cleansing storm sewers. *Water Science and Technology*, 33(9), 215-220, 1996.
58. Nielsen P.H. Raunkjær K., Norsker N.H., Jensen N.A., Hvitved-Jacobsen T.: Transformation of wastewater in sewer systems. *Water Science and Technology*, 25(6), 17-31, 1992.
59. Ociepa E. Ocena zanieczyszczenia ścieków deszczowych trafiających do systemów kanalizacyjnych. *Inżynieria i Ochrona Środowiska*, 14(4), 357-364, 2011.
60. Ociepa E., Kisiel A., Lach J.: Zanieczyszczenia wód opadowych spływających do systemów kanalizacyjnych. *Proceedings of ECOpole*, 4(2), 465-469, 2010.
61. Orhon D., Ates E., Sozen S., Cokgor E.U.: Characterization and COD fractionation of domestic wastewater. *Environmental Pollution*, 95(2), 191-204, 1997.
62. Orzechowski Z., Prywer J., Zarzycki R.: Mechanika płynów w inżynierii środowiska. WNT, Warszawa 2001.
63. Palarski J.: Hydrotransport. WNT, Warszawa 1982.
64. Park M.-H., Swamikannu X., Stenstrom M.K.: Accuracy and precision of the volume-concentration method for urban stormwater modeling. *Water Research*, 43, 2773-2786, 2009.
65. Płuciennik S., Wilbik J.: Warunki techniczne wykonania i odbioru sieci kanalizacyjnych. Wymagania Techniczne COBRTI Instal, Zeszyt 9, Warszawa 2003.

66. Pomeroy R.D., Parkhurst J.D.: Self-purification in Sewers. VI International Conference, Advance in Water Pollution Research – Jerasalem, 1972, 291-308, Pergamon Press, Oxford, New York, Toronto, Sydney, Braunschweig 1973.
67. Puzyrewski R., Sawicki J.: Podstawy mechaniki płynów i hydrauliki. PWN, Warszawa 2000.
68. Roman M.: Kanalizacja – oczyszczanie ścieków Tom 2. Arkady, Warszawa 1986.
69. Rossman L.A.: Storm Water Management Model – User's manual, version 5.0. Water Supply and Water Resources Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati 2010.
70. Rudziewicz I.: Wybierając system... *Wodociągi-Kanalizacja*, 2/2006, 21, 2006.
71. Rup K.: Mechanika płynów w środowisku naturalnym. Wydawnictwo Politechniki Krakowskiej, Kraków 2003.
72. Rutkowski T.: Od modelowania, przez symulację do sterowania. *Wodociągi-Kanalizacja*, 10/2005, 12-15, 2005.
73. Rybicki S.A., Rybicki S.M.: Odprowadzanie i oczyszczanie wód deszczowych w strefach ochronnych ujęć wody. *Ochrona Środowiska*, 1(80), 3-8, 2001.
74. Sawicki J.: Przepływy ze swobodną powierzchnią. PWN, Warszawa 1998.
75. Sawicki J.M.: Migracja zanieczyszczeń. Wydawnictwo Politechniki Gdańskiej, Gdańsk 2003.
76. Shanahan P., Borchardt D., Henze M., Rauch W., Reichert P., Somlyódy L., Vanrolleghem P.: River water quality mode No.1: I Modelling approach. *Water Science and Technology*, 43(5), 1-9, 2001.
77. Siwoń Z.: Symulacyjne modele przepływów w systemach dystrybucji wody - problemy kalibracji i weryfikacji modeli. GIS - modelowanie i monitoring w zarządzaniu systemami wodociągowymi i kanalizacyjnymi, Warszawa, 157-189, 2005.
78. Skotnicki M.: Komputerowe modele sieci kanalizacyjnych - program SWMM 5.0. *Przegląd Komunalny*, 5, 76-78, 2005.
79. Soczyńska U. (red.): Hydrologia dynamiczna. PWN, Warszawa 1997.
80. Soonthornnonda P., Christensen E.R.: Source apportionment of pollutants and flows of combined sewer wastewater. *Water Research*, 42, 1989-1998, 2008.
81. Sophonsiri C., Morgenroth E.: Chemical composition associated with different particle size fractions in municipal, industrial, and agricultural wastewaters. *Chemosphere*, 55, 691-703, 2004.
82. Stelmach K., Malicki J., Bonetyński K.: Kolektory - rozcieńczanie czy redukcja BZT₅ i biogenów. (w:) Materiały Międzynarodowej Konferencji Naukowo-Technicznej, Współczesne problemy gospodarki wodno-ściekowej, Wydawnictwo Uczelniane WSI Koszalin, Koszalin-Kołobrzeg, 429-434, 1995.
83. Suligowski Z.: Kanalizacja. Wydawnictwo Uniwersytetu Warmińsko-Mazurskiego, Olsztyn 2000.

84. Szpindor A.: *Zaopatrzenie w wodę i kanalizacja wsi*. Arkady, Warszawa 1992.
85. Szymkiewicz R.: *Modelowanie matematyczne przepływów w rzekach i kanałach*. PWN, Warszawa 2000.
86. Walden H., Stasiak J.: *Mechanika cieczy i gazów w inżynierii sanitarnej*. Arkady, Warszawa 1971.
87. Widomski M.K., Musz A., Gajuk D., Łagód G.: Numerical modeling in quantitative and qualitative analysis of storm sewage system extension. *Ecological Chemistry And Engineering A*, 19(4-5), 471-481, 2012.
88. Wosiewicz B.: O modelowaniu i modelach numerycznych zjawisk hydraulicznych. *Gospodarka wodna*, 3, 74-85, 1996.
89. Wotherspoon D.J.J., Ashley R.M.: Rheological measurement on the yield strength of combined sewer deposits. *Water Science and Technology*, 25(8), 165-169, 1992.
90. Zawilski M., Sakson G.: Wykorzystywanie programu SWMM w modelowaniu systemów kanalizacyjnych. w: *Praca zbiorowa pod red. J. Łomotowskiego Problemy zagospodarowania wód opadowych*, Seidel-Przywecki, Wrocław 2008.
91. Zoppou C.: Review of urban storm water models. *Environmental Modelling & Software*, 16, 195-231, 2001.
92. Żelaziński J.: Symulacja komputerowa jako metoda badania strategii ochrony przeciwpowodziowej. Przyjazna środowisku strategia ochrony przed powodzią. http://tnz.most.org.pl/dokumenty/publ/psopp/imgw_w4.htm (2013)

www

93. www.sewerhistory.org/chron.htm (15.03.2013)
94. www.dziobak.pl/hydro/projekty/sola/sola.html (15.03.2013)
95. <http://sjp.pwn.pl> (15.03.2013)