Artículo de investigación

Trends in studying urban runoff: a retrospective analysis

Tendencias en el estudio de la escorrentía urbana: un análisis retrospectivo
Tendências no estudo do escoamento urbano: uma análise retrospectiva.

Recibido: 20 de abril de 2018. Aceptado: 10 de mayo de 2018

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Abstract

The paper is a retrospective analysis of trends in quantitative empirical and theoretical studies of urban surface runoff from the mid-19th century to the early 90s of the 20th century, when the largest Soviet scientific school for such studies in the city of Kharkov was dissolved. As shown in the paper, the calculation methods for estimating peak discharges of urban surface runoff can be traced back to a pioneering work by T.J. Mulvaney (1850), which laid the foundation for the "rational method". Later this method was developed in the works by E.Kuichling (1889) and D.E.Lloyd-Davies (1906). The significance of developing such a method was determined by frequent cases of flooding urban territories and by the need for rapid removal of large volumes of storm water through special collectors. This method is still widely used in simplified calculations of urban surface runoff, since it has a good physical justification (balance equation): the amount of precipitation falling on a given catchment area equals the amount of runoff less losses for infiltration, surface retention and evaporation, which are integrally included into a surface runoff coefficient. Along with accumulating empirical data, scientists began to pay more attention to the problem of pollution of urban surface runoff, as it causes pollution of rivers, lakes, seas, water storage reservoirs and other water bodies. First of such systematic studies were commenced in

Resumen

El artículo es un análisis retrospectivo de tendencias en estudios empíricos y teóricos cuantitativos de escorrentía superficial urbana desde mediados del siglo XIX hasta principios del siglo XX, cuando se disolvió la mayor escuela científica soviética para tales estudios en la ciudad de Kharkov. Como se muestra en el documento, los métodos de cálculo para estimar las descargas máximas de la escorrentía superficial urbana se remontan a un trabajo pionero de T.J. Mulvaney (1850), que sentó las bases del "método racional". Más tarde, este método fue desarrollado en los trabajos por E.Kuichling (1889) y D.E.Lloyd-Davies (1906). La importancia de desarrollar tal método fue determinada por los frecuentes casos de inundación de los territorios urbanos y por la necesidad de una rápida eliminación de grandes volúmenes de agua de lluvia a través de colectores especiales. Este método todavía se usa ampliamente en cálculos simplificados de escorrentía superficial urbana, ya que tiene una buena justificación física (ecuación de equilibrio): la cantidad de precipitación que cae en un área de captación dada es igual a la cantidad de escorrentía menos pérdidas por infiltración, retención de superficie y evaporación , que se incluyen integralmente en un coeficiente de escorrentía superficial. Junto con la acumulación de datos empíricos, los científicos comenzaron a the 60-70s of the 20th century by the US governmental agencies. Having accumulated a large amount of empirical data and having understood the mechanisms determining the water quality of urban surface runoff, scientists began to develop continuous simulation models, which the paper reviews and dwells on.

Keywords: balance equation, continuous simulation models, peak discharges, rational method, surface runoff coefficient, urban surface runoff.

prestar más atención al problema de la contaminación de la escorrentía superficial urbana, ya que causa la contaminación de ríos, lagos, mares, depósitos de almacenamiento de agua y otros cuerpos de agua. El primero de tales estudios sistemáticos se inició en los años 60-70 del siglo 20 por las agencias gubernamentales de los Estados Unidos. Habiendo acumulado una gran cantidad de datos empíricos y habiendo entendido los mecanismos que determinan la calidad del agua de la escorrentía de la superficie urbana, los científicos comenzaron a desarrollar modelos de simulación continuos, que el artículo revisa y continua.

Palabras clave: ecuación de equilibrio, modelos de simulación continua, descargas máximas, método racional, coeficiente de escorrentía superficial, escorrentía superficial urbana.

Resumo

O artigo é uma análise retrospectiva das tendências em estudos teóricos e empíricos quantitativos de escoamento urbano de meados do século XIX ao início do século XX, quando a maioria escola científica soviética para tais estudos foi dissolvida na cidade de Kharkov. Como mostrado no papel, os métodos de cálculo para estimar as descargas máximas do escoamento superficial urbano podem ser rastreados até um trabalho pioneiro do T.J. Mulvaney (1850), que lançou as bases do "método racional". Mais tarde, este método foi desenvolvido nos trabalhos de E. Kuichling (1889) e D. E. Lloyd-Davies (1906). A importância do desenvolvimento de tal método foi determinada pela freqüente inundação de territórios urbanos e pela necessidade de uma rápida eliminação de grandes volumes de água da chuva através de coletores especiais. Este método ainda é largamente utilizado em cálculos simplificados de escoamento urbano, e que tem o bom justificação física (equação de equilíbrio): a quantidade de precipitao que cai sobre uma determinada área de captação é igual à quantidade de escoamento de menos infiltração retenção de superfície e evaporação, que estão integralmente incluídos em um coeficiente de escoamento superficial. Junto com o acúmulo de dados empíricos, os cientistas começaram a prestar mais atenção ao problema da poluição por esgoto urbano, porque faz com que a poluição de rios, lagos, mares, tanques de armazenamento de água e outros organismos aquáticos. O primeiro desses estudos sistemáticos foi iniciado nos anos 60 e 70 do século 20 por agências governamentais nos Estados Unidos. Tendo acumulado uma grande quantidade de dados empíricos e tendo compreendido os mecanismos que determinam a qualidade da água de escoamento da superfície urbana, os cientistas começaram a desenvolver modelos de simulação contínuas, os comentários do artigo e pára.

Palavras-chave: equação de equilíbrio, modelos de simulação contínua, vazões máximas, método racional, coeficiente de escoamento superficial, escoamento superficial urbano

Introduction

Currently the problem of studying, modeling and controlling over urban runoff is quite urgent. The impact of urban runoff on the pollution of water bodies is comparable to or even exceeds the impact from the liquid industrial or household fecal wastewater on them. The problem is aggravated by the fact that urban runoff is not regular and hard to forecast, as it depends on stormwaters and snow melting, which in term resulted in the introduction of concept of “design storm”. The phenomenon of urban runoff was first noticed by specialists in late 19–early 20 centuries, in the context of flooding in urban areas and the need to quickly drain urban storm water through special water collectors. This paper presents a retrospective analysis of trends in quantitative studies of urban runoff from the moment when such studies appeared till the 90s of the 20th century, when the Soviet scientific school of studying urban runoff, the center of which was located in Kharkov, was destroyed (The All-Union Research Institute of Water Conservation). By a quantitative study of urban runoff we mean field and experimental studies and mathematical modeling of urban runoff constructed on their base.

Methods

The current research is shaped as a retrospective analysis of studies of urban runoff, for which Google Scholar will be used. Through Goolge Scholar, we will identify the key works in this research area, including the first papers, and carry out their qualitative analysis. Doing so, the focus will be placed on quantitative methods of studying urban runoff and its mathematical simulation. In the conclusion, we will give an account of the achievements of the Soviet school of studying urban runoff, considering the fact that they have never been reported in foreign journals, while scientifically they were as valuable as foreign achievements, primarily those from the American scientific school.

Results and Discussion

One of the oldest and most basic methods of calculating urban runoff, which has survived till present, is a "rational method". According to Dooge (1957), the principles of the "rational method" were established by T.J.Mulvaney in 1850. Mulvaney's work was based on rainfall-runoff data collected on arterial drainage basins in Ireland (Mulvaney 1850). In 1889, the peak-discharge formula now known as the "rational formula" was proposed by E.Kuichling (1889). Kuichling's work was based on urban areas and was proposed for estimating peak discharge in U.S. sewage systems. U.K. equivalent of rational formula was offered by D.E.Lloyd-Davies in 1906 (Lloyd-Davies 1906).

The rational method of predicting a design peak runoff rate is expressed by the equation $Q = C\,i\,A$, where Q –design peak runoff rate in cubic feet per second, C – runoff coefficient, i – rainfall intensity in inches per hour for the design recurrence interval and for a duration equal to the "time of concentration" of the watershed, A – watershed area in acres (Schwab et al. 1966).

The "time of concentration" is defined as the time required for water to flow from the most remote point of the watershed to the outlet. The runoff coefficient, C, is defined as the ratio of the peak runoff rate per unit area to the rainfall intensity. Empirical procedures are available for estimating these parameters (Schwab et al 1966).

Before 1925, the main objective of rainfall-runoff research on small drainage basins was the prediction of the peak discharge due to a given or design rainfall. Due to a very limited knowledge of rainfall-runoff processes and a very limited amount of reliable data, proposed techniques were based mostly on empiricism (Schmer 1969).

During the latter part of the 1920s design engineers realized that the time distribution of the flow was important. This led to the development of time-area and routing methods for determination of basin flow. Development of the time-area diagram (curve) involves the vision of the basin into zones through the use of isochrones of the travel time from selected points to the basin outlet (Schmer 1969). Use of this methods is described by Linsley et al. (Linsley et al. 1958), and continues to be used widely today.

In 1930, L.Metcalf and H.P.Eddy (Metcalf, Eddy 1930) introduced the zone principle in urban hydrology. In 1932, Scherman (Scherman 1932) introduced the concept of the unit graph. This approach, known today as the unit-hydrograph approach, has been the basis for almost all methods used in prediction of stream flow (Schmer 1969). Today it is one of the most powerful instruments in urban hydrology.

As conceived by Scherman (Scherman 1932), in its empirical nature, this unit-hydrograph approach was based on the following assumption (Schmer 1969).

1. For a given watershed, runoff producing storms of equal duration will produce surface-runoff hydrographs with an equal time base, regardless of the intensity of the rainfall.
2. For a given watershed, magnitude of the ordinates representing the instantaneous discharge from an area will be proportional to the volume of surface runoff produced by storms of equal duration.
3. In a given watershed, the time distribution of runoff from a given storm period is independent

of precipitation from antecedent or subsequent storm periods.
Whereas application of the rational formula is limited generally to small areas, the unit-hydrograph method does not suffer from such a restriction (Schmer 1969).

At the same time, in Gregory&Arnold (1932) it is stated that the rational formula is especially true for large natural basins. The conclusions of (Schmer 1969) are contradicted by an earlier study by W.-W. Horner (1933), which notes that "the unit graph" can be satisfactorily prepared for the runoff from single city block and that this graph would be applicable through a considerable range of rates of precipitation. The large problem is to find a way in which a satisfactory "unit graph" may be readily produced for urban watersheds of considerable extent (Horner 1933).

It should be mentioned that in the Soviet period, when carrying out aggregate calculations of urban surface runoff for the purposes of planning water-protective measures and regulating the release of runoff into water bodies, they used solely the rational formula (Pravila ohrany 1975; Khvat 1983).

In 1932, R.-L. Gregory and C.-E.Arnold (Gregory&Arnold 1932) improved this formula by introducing seven parameters instead of three. As the new four parameters they considered: P- reflecting the shape of the area and manner of concentration, F – reflecting the shape and condition of the main channel, L – distance the water must travel in running from the most remote points of the watershed to its outlets, I – slope of channel. This formula is knows in the literature as the general rational formula (Delleur 1982).

A further development of the unit-hydrograph approach was the following. One of the first procedures developed for synthetic construction of a unit-hydrograph was presented by Snyder in 1938 (Snyder 1938). Snyder worked on rainfall-runoff data for streams in the Appalachian Highlands and correlated the basin characteristics with peak flow, basin lag, and total time base of the unit-hydrograph (Schmer 1969).
In 1945, Clark (Clark 1945) suggested that the unit-hydrograph for instantaneous rainfall excess, i.e., the instantaneous unit-hydrograph (unit-impulse), could be derived by routing the time-area-concentration curve through a linear storage reservoir (Schemr 1969).

Nash's approach to obtaining an instantaneous unit-hydrograph aroused considerable interest and discussion (Nash 1959). By routing the unit-impulse input through a series of ***n*** equal linear reservoirs, Nash developed an expression for the instantaneous unit-hydrograph. As noted in (Schmer 1969), Nash equation is very similar to that proposed by Edson in 1951 (Edson 1951).

A great contribution into the development of the unit-hydrograph approach and its application to urban hydrology was made by Eagleson and March (1965) and Viessman (1966, 1968). The earlier studies had been conducted by P.Bock and W.Viessman (1958) on Inlet hydrograph and A.L.Tholin and C.J.Keifer (1960) on Chicago hydrograph methods.

To further develop the rational and unit-hydrograph approaches, W. I. Hicks in 1944 designed the Method of Computing Urban Runoff, in which he proposed a formula for calculating the time of overland flow (Hicks 1944).

$$t_c = \frac{C_r l^x}{Q^y s^z}$$, where

t_c – min; l – flow length in feet, Q – supply rate of rainfall excess, inches/hour; s - surface slope angle, %; C_r, x, y, z – empirical constants depending on the slope surface. W. I. Hicks provides a table of these constants for three types of surfaces.

In Izzard (1946), the experiments conducted by W. I. Hicks were tested on the airport drainage. When computing the flows in collectors, W. I. Hicks (1944) used Manning's formula. The Method of Computing Urban Runoff, suggested by W.I. Hicks is also known as the Los Angeles hydrograph (Delleur 1982).

It should be noted the reviews of the earlier studies on this topic are given in dissertations by K.P.Singh (1962) and V.C. Kulandaiswamy (1964). All the major achievements in developing engineering methods of computing urban runoff by the late 1940s were summarized in Hydrology Handbook (1949), and by the early 1960s – in Handbook of Applied Hydrology (1964).

A further step forward on the way of developing methods for computing urban runoff was the British Road Research Laboratory Method (RRL Model), proposed in 1962 (Watkins 1962). This method utilizes the time-area curve and the hyetograph of rainfall excess to determine surface runoff hydrographs. The surface runoff hydrograph is then routed through a storm drainage network by the simple storage routing method. The British RRL Model considered only the runoff from impervious areas. The model yields satisfactory results if (1) the watershed areas are smaller than 12.95 km^2 (5 miles^2) and (2) the impervious areas directly connected to the sewer network comprise more than 15% of the total area (Stall, Terstriep 1972; Fok, Murabayashi, Phamwon 1977).

In Terstriep&Stall (1969) this model is tested on three urban watersheds in the U.S. The basins are located in Baltimore, Chicago, and Champaign, Illinois. The model produces a runoff hydrograph by applying rainfall to only the directly connected impervious area of the basin. The basin is described by a time-area diagram and a discharge-storage relationship. The peak discharges of actual and predicted hydrographs are compared for 39 storms and complete hydrographs are shown for 8 of these. To apply the model to a basin, the pattern of impervious areas must be known in detail, as well as the slopes and sizes of all surface and subsurface drains.

Basing on the British RRL Model, M.L.Terstriep and J.B.Stall (1974) developed the Illinois Urban Drainage Area Simulator (ILLUDAS). It includes runoff from pervious as well as impervious areas, as contrasted to the British RRL Model. The ILLUDAS Model yields fairly accurate results for urban watershed having less than 25.9 km^2 (10 miles^2) in area and more than 20% in paved area (Fok, Murabayashi, Phamwon 1977).

In the latter paper, there was offered a model in question which was modified to fit the Hawaiian urban watersheds. Since most of the Hawaiian small urban watersheds are less than 25.9 km^2 and have more than 20% impervious surface area, the ILLUDAS Model is expected to be adaptable to the Hawaiian small urban watersheds. Since this study emphasizes the procedures for (1) channel flow routing through gutters and storm drains and (2) runoff routing from pervious and impervious areas, the first task was to modify the overland, gutter, and sewer flow routing procedures of the ILLUDAS Model. This was accomplished by utilizing the kinematic wave equation which is believed to be a suitable method for a steep topographic terrain, such as that in the study area. The second task was to modify the infiltration process by utilizing available infiltration data (Fok, Murabayashi, Phamwon 1977).

Unlike the previously considered methods of computing urban runoff and constructing its hydrograph, the British RRL and ILLUDAS Models are digital computer (simulation) models.

To this class of models, we can also include a systems model of urban storm water runoff by FWQA (The US Federal Water Quality Association), which consists of a particular model of urban storm water runoff and a model of its transformation in the channel network. The basin in divided into several smaller watersheds, whose hydraulic and geometric properties have to be known (areas, widths, slopes, Manning's roughness coefficient, infiltration intensity, surface tension layers). The model is suitable for constructing a hydrograph of runoff from watersheds having a collector center of up to 30 inches in diameter.

According to Linsley (1971), as of the early 1970s, there were more than ten computer-based simulation models which were capable of simulating urban storm-runoff. If these models are classified according to the time element upon which they are based, they can be sorted into two groups, namely, the continuous simulation model, and the discontinuous simulation model. The former continuous simulation model should include the Stanford Watershed Model (Crawford, Linsley 1966), which in turn includes comprehensive hydrologic factors for a continuous water-balance simulation. Therefore, it requires a computer capable of powerful and wide array of input data for the numerous coefficients of the simulation model. So, this type of model would serve very well for comprehensive watershed planning. On the other hand, the discontinuous simulation models simulate the hydrologic process on an event basis; therefore, many time-response delaying hydrologic factors have been excluded from this type of model. As a result, the computer programs of the discontinuous simulation model are much simpler than those of the continuous simulation models (Fok, Murabayashi, Phamwon 1977).

Computer software for Stanford Watershed Model (SWM) was being developed from 1959 to 1966. In 1974, work resulted in the widely available codes known as the Hydrologic Simulation Program Fortran (HSPF), developed for and with support of the young U.S. Environmental Protection Agency. This model used block infiltration and evaporation, as well as kinematic wave routing for channel flows (Crawford, Burges 2004).

At the same time (1973-1976), in Hydrological Unit of University of Witwatersrand (Johannesburg, South Africa), based on SWM IV there were obtained three versions of HRU model – on a monthly, daily and hourly basis (Pitman 1973, 1976)

In the late 1960s – early 1970s, the processes of initial retention (or initial loss) and infiltration capacities of the pervious surfaces were actively studied. Thus, in Brater (1968), by the example of drainage basins, varying in size from 9.5 to 185 square miles, located in the Detroit metropolitan area, it was shown that infiltration capacities in this region are from 3 to 5 times higher in late summer that in early spring, and the average initial retention for the basins studied is approximately 0.2 inch.

In Viessmann et al (1970), the latter indicator was obtained at the level of 0.1 inch. In that study there were studied exponentially decaying loss functions, similar to Horton infiltration function.

The results of these and other studies made up an empirical basis for constructing and calibrating various continuous simulation models.

Along with urban growth and consequent pollution loads on urban territories, specialists started to notice that urban runoff had negative impact on the receiving water bodies. The first to conduct systematic studies in this area was the Cincinnati Water Research Laboratory, U.S. Department of the Interior, whose employees had their papers published in the Journal of Water Pollution Control Federation (Weibel, Anderson, Woodward 1964; Evans, Geldreich, Weibel, Robeck 1968).

Thus Evans, Geldreich, Weibel, Robeck (1968) stated that urban stormwater runoffs contain constituents of a character hazardous to public health. Samples of stormwater runoff from a separately sewered residential-light commercial area of Cincinnati taken from 50 storms over 2 years contained suspended solids, 5 to 1,200 mg/l; volatile suspended solids, 1 to 290 mg/l; BOD, 1 to 170 mg/l; and COD, 20 to 610 mg/l. Total coliform densities exceed 2,900/100 mg in 90 percent of the samples. Fecal organisms in varying densities were found in the runoff. Two to 6 mg/l of chlorine and 20-min contact time were necessary to kill 99.99 percent of total coliforms or fecal streptococci. The results these studies emphasize is the importance of fecal coliforms rather than total coliforms, as a more realistic microbial indicator of pollution.

Similar studies were carried out in the late 1960s-early 1970s by the American Public Works Association and Avco Economic Systems Corporation. Those studies were conducted under the contract with the Federal Quality Administration, Department of the Interior, USA. Thus, in the American Public Works Association Report (1969), there were analyzed samples of surface runoff from the lower part of Detroit: total solids concentration, 310 to 964 mg/l; suspended solids concentration, 102 to 213 mg/l; BOD, 90 to 234 mg/l.

With the first empirical data on the water quality of urban runoff having been collected and the main mechanisms of its formation having been studied, scientists started looking for ways to incorporate the data and mechanisms in continuous simulation models mentioned earlier.

Linsley and Crawford (1974) present a useful discussion of continuous simulation in urban hydrology. Among the earliest of the continuous simulation models was Stanford Watershed Model (Crawford, Linsey 1966), out of which evolved the Hydrocomp Model (Hydrocomp, 1976), a versatile program for natural and agricultural as well as urban areas (Huber 1979). This model, also known as Hydrologic Simulation Program, written in Fortran language (HSPF), was developed, as we mentioned earlier, in 1974. Unlike Stanford Watershed Model, it has algorithms to calculate accumulated pollution loads on urban territories and their washout during rainfall events and snow melting periods. Hydrocomp Model uses a 15-minute time step, as does the Dorsch QQS Model (Geiger et al. 1976).

Wayne C. Huber (1979) thought that probably the most widely used continuous simulation model for urban areas is STORM (STORM, 1976; Roesner et al. 1974), developed by Water Resources Engineers, the City of San Francisco, and the Hydrologic Engineering Center of the Corps of Engineers. It uses one-hour time steps coupled with simplified runoff and pollutant estimation procedures and has been extensively used for planning (e.g. Roesner et al. 1974) and overall urban runoff evaluation (e.g. Heaney et al. 1977). A similar, but even simpler model, still producing useful statistics of long-term urban runoff is the Simplified Storm Water Management Model (Huber 1979). This model was developed by Metcalf and Eddy (1971). Wayne C. Huber (1979) also mentioned that several "first cut" procedures had been developed, based in part upon continuous, but avoiding any computer usage at all (Howard 1976; Heaney et al. 1976; EPA 1976).

So, having accumulated the first empirical data on the water quality of urban runoff, scientists set out to develop systems (simulation) mathematical models to form the water quality of urban surface runoff basing on a continuous simulation approach. The earliest model of this kind mentioned above was Storm Water Management Model (SWMM). Its first version was published in 1971, a second one in 1975, a third – in 1981, a fourth – in 1988-1992, and a fifth – in 2004. The Applied Manual for using the fifth version of the model put into effect in 2005 was published in 2009. It should be noted that the main developer of the competing STORM Model – L.A. Roesner – in 2009 was among the authors of the Applied Manual (2009) for SWMM Model. This fact along with the five versions of SWMM and its use in both developed in developing countries, which was proved by our experiments with help of Google Scholar, indicates that now there is a properly tested simulation mathematical model to form the water quality of urban runoff, suitable for trying out various scenarios of forming such quality and of contaminated urban runoff influencing water bodies.

Besides this type of simulation models, in 1980, there was suggested Macroscopic Planning Model (ABMAC) (Litwin, Lager, Smith 1980), which combined a rational method of calculating runoff volume: $R = kAr$ and a formula to calculate the washout of contaminating matters by surface runoff: $M = CR$. In these formulas R is runoff volume, k is a runoff coefficient, r is a rainfall layer, A is a catchment area, C is an average concentration of contaminating matters and M is mass of contaminating matters washed out by surface runoff.

The USSR lagged behind in this respect and started empirical studies of water quality of urban runoff shortly after the creation in 1971 of the Urban Runoff Laboratory in the All-Union Research Institute of Water Conservation (Kharkov). As Kharkov was a twin-city of Cincinnati (USA), it became possible to obtain all the major EPA reports from the latte, which promoted progress in studying this problem.

In the mid-1970s, all the main regulations for the Ministry of Water Resources of the USSR to prevent water pollution by urban runoff were developed. Further field studies were quite effectively combined with experiments (a rain simulator "Runoff") and mathematical simulation. The results of those studies were widely used in the Soviet practice of evaluating the impact of urban runoff on water bodies, planning water-control measures and designing treatment facilities for surface runoff from urban areas and industrial sites. Unfortunately, the findings of that research have never been published in English and failed to become known to foreign professionals. In the current paper we will try to address this gap in terms of continuous simulation modeling. As the ideological basis for this research, the Soviet urban runoff school used the major statements from (Modelling Nonpoint Pollution 1976):

1. Need of using deterministic models, because due to complex links and limited data from field studies, statistical models are not effective when evaluating nonpoint pollution sources (extrapolation to other geographical regions or conditions is frequently impossible);
2. In continuous simulation modeling, great importance should be attached to rainless periods;
3. Continuous simulation of nonpoint pollution is similar to a "three-layer" pyramid, having hydrology in its basis, the modeling of erosion and sediment transport as its middle layer and as its top – an interaction of various pollutants with liquid and solid runoff phases, resulting in their transport.

Additionally to the third statement, it was assumed that transport of chemicals by urban runoff was carried out mainly on suspended solids. It allows confining oneself to constructing a model of washout suspended solids (Moskovkin, Lysenko, Kolpak 1983).

The methodology of continuous simulation of nonpoint pollution is extensively combined with the systems methodology in terms of allowing for a great number of parameters, processes and factors, their relations and spatial distribution through sub-catchment areas, the realization of which requires powerful computing means with extensive memory and speed. The analysis of foreign studies in mathematical modeling of urban runoff formation and its quality from (Moskovkin, Lysenko, Kolpak 1983) showed that the models that had been built by then were based on the following principles (Amy et al. 1974; Donigian, Crawford 1979; Modelling Nonpoint Pollution 1976; Metcalf and Eddy 1971; STORM, 1976):

- dividing an urban area into separate zones depending on a type of land use (American models NPS, SWMM, STORM);
- distinguishing between the main channel and the sewer system (SWMM, STORM models), used for the concentrated surface runoff discharge (in a STORM model the main channel is not distinguished);
- viewing an urban area with scattered runoff of surface water as one equivalent catchment area, and built-up pollutants are accumulated according to a type of land use (Canadian LQM model);
- the calculation of the initial pollution load is carried out considering a daily rate of accumulated road dust, rainless periods and street cleaning (NPS, SWMM, STORM, LQM models); various structures of computational relations are applied;
- the calculation of surface runoff is based on continuous balance models (for NPS, SWMM, LQM models); runoff rate method (runoff calculation on a hourly basis) and an unit hydrograph methods (to calculate outlet hydrographs for each sub-catchment area (STROM model);
- the calculation of pollution runoff is based on the methodology by L.Metcalf and H.P.Eddy (1930), according to which the intensity of pollution runoff, including that of suspended solids, is proportional to the amount of matters on the surface (SWMM, LQM, STORM models), and the use of empirical coefficients considering a share of each matter washed out by a solid phase of runoff (NPS model), where the solid phase of runoff is calculated by power law for a liquid phase or is equal to the volume of sediments accumulated over a rainless period under study.

However, these models turned out to be too complicated to be widely used in the Soviet period (when the information was either missing or unsuitable for use). That is why the main principles the above models were based on had to be transformed and elaborated in the following way:

- an urban area was divided into zones within which the annual rate of accumulated road dust (V, kg/m^2 per year) and a runoff rate are the same;
- the computation of pollutant washout was carried out for each zone to estimate their contribution into the overall washout;
- the computation of an initial pollution load was carried out with use of a STORM model equation (STORM 1976) modified in (Moskovkin, Lysenko, Kolpak 1983) and for uncleaned areas this load can be calculated by means of road dust balance equation offered in (Moskovkin, Lysenko, Kolpak 1983), which considers road dust consolidation and its inaccessibility for transporting by a water flow;
- for the sake of simplicity, to a first approximation, computation of surface runoff is based on rational formulae (in Soviet terminology – runoff coefficient method), while the computation of road dust washout over is based on a conventional and more reasonable Metcalf & Eddy equation (Metcalf and Eddy 1971).

A numerical algorithm offered of a simplified model was realized on the PL1 language in form of a standard procedure, using which some numerical experiments were conducted for the conditions of the City of Kharkov. Most parameters were obtained according the scheme of city street sanitation and clean-up while dividing the urban territory into four typical sections with cleaned and uncleaned areas. The computation results were consistent with the data obtained through field studies by the Urban Runoff Laboratory of All-Union Research Institute of Water Conservation. For example, the average concentration of suspended solids in urban runoff, obtained through processing the data from field studies of 1973 in Kharkov (Bukholdin et al. 1974) was 1570 mg/l, which fitted the design concentration (Moskovkin, Lysenko, Kolpak 1983).

Whereas in the above model the washout of suspended solids is calculated according to the exponential solution of the Metcalf & Eddy equation for the entire rain event, in the advanced model (Moskovkin, Vavelskij, Khvat 1988) a runoff layer in the solution of this equation was considered time-dependent and determined by solving the water balance equation (slope length averaged continuity equation for flow water). The water balance equation was viewed as a nonlinear ordinary differential equation for the value of the runoff layer, which was proposed in (Moskovkin, Lysenko, Kolpak, Kurnosenko 1983). For the numerical implementation of this equation by means of a Runge–Kutta method in (Kolpak, Moskovkin, Lysenko 1984) there was developed a standard FLOW procedure in the PL1 language.

On the basis of this advanced simulation model, there was conducted a continuous simulation of the formation of surface runoff and its quality for the territory of the Tiraspol Meat Processing Plant (Moldova) for five consecutive rain events that occurred from June to August 1982. The result showed good convergence of the data obtained through field measurements with those received from mathematical modeling (Moskovkin, Vavelskij, Khvat 1988).

The Soviet school of studying urban runoff was also good at solving the task of the quantitative assessment of pollutant loads in urban areas, depending on pollution sources - wear of road surface due to traffic, wear on tires, washout of suspended solids from pervious areas and impervious areas, as well as aerosol deposition (Khvat, Moskovkin 1989; Khvat, Moskovkin 1991). The problem of computing aerosol deposition was worked out in depth (Khvat, Moskovkin, Manuyulov, Ronenko 1991; Kondratyev et al. 1991).

All of the above theoretical studies formed the basis for the concept of creating local drainage and urban runoff treatment systems, based in turn on two principles: 1. ranking the urban area according to the degree of contamination and disposing of runoff from the most contaminated areas for treatment; 2. treatment facilities to treat the most contaminated urban runoff first. Both points define the criteria to determine from which areas to remove runoff for treatment and what portions of runoff from contaminated areas should be treated first.

Both of these principles were used in practice to design surface runoff treatment facilities.

Thus, the Soviet scientific school of urban runoff studies, initially guided by the achievements of the American scientific school, made a substantial advance. Unfortunately, after the USSR dissolution, these studies were discontinued, and only now we are making an attempt to revive them, as the current paper shows.

Conclusions

The paper is a retrospective analysis of trends in quantitative studies of urban runoff from their inception in the second half of the 19th century to the early 90s of the 20th century, when the Soviet scientific school studying the processes of urban runoff based in the city of Kharkov was destroyed.

For over a century, the phenomenon of urban runoff was considered solely in the context of the flooding of urban areas and a necessity to rapidly dispose of urban storm water through special water outlet collectors.

Along with urban growth and consequent polluting loads on urban territories, specialists started to notice that urban runoff had negative impact on the host water bodies. The first systematic studies in this field were started in the 60s-70s of the 20th century by US government agencies.

With the first empirical data on the water quality of urban runoff having been collected and the main mechanisms of its formation having been studied, scientists started looking for ways to incorporate the data and mechanisms in continuous simulation models.

Further we gave a detailed analysis of contribution to the issue by the Soviet scientific school on the quantitative study of urban runoff, which was based in the All-Union Research Institute of Water Conservation (now Ukrainian Research Institute of Ecological Problems, Kharkov, Ukraine) and existed from the early 70s to the early 90s of the 20th century.

There was also shown that the Soviet scientific school of urban runoff studies, initially guided by the achievements of the American scientific school, made a substantial advance, which has failed to become known to the foreign scientific community as the results have never been published in English before.

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