Designing drainage systems – possible application of advanced calculations and hydrodynamical modeling

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Abstract: Nowadays we can observe a faster development of drainage systems than ever. This gives us an opportunity to design more efficient systems that can cope with the rapid growth of cities and, what comes with it, impervious surfaces. Here the question arises, whether traditional methods used in drainage system design are potent enough to cope with the emerging problems and difficulties. In this paper we will make a short overview of the traditional drainage design process. We will focus on its usefulness in solving more complicated tasks and we will propose a few alternatives. We will also look at the pros and cons of the presented methods with respect to limitations imposed by the design process. At the end we will discuss shortly if they are truly useful in solving engineering problems and in the design process.

1. Introduction

Nowadays we can observe a faster development of technology and infrastructure than ever. Drainage systems are no different. New armature, devices or even whole rainwater solutions appear each year on the market. This gives us an opportunity to design more efficient systems that can cope with the rapid growth of cities and, what comes with it, impervious surfaces. But this development also means an increasing difficulty of the task. Here the question arises whether traditional methods used in drainage systems design are potent enough to cope with the emerging problems and difficulties.

In this paper we will make a short overview of a few approaches that can be alternative to traditional drainage design methods commonly used in Poland. We will also look at the pros and cons of the presented methods with respect to limitations imposed by the design process.
2. Traditional drainage systems design

Designing a drainage system is a process consisting of a few steps none of which can be skipped. In many cases there is a need of more than one designer to participate in the process. One of the reasons for that is the multi-branch character of the design process. For example, while most of the work is done by sanitary engineers, part of the work is also done by road engineers because the location of the inlets is closely connected to surface designing. The main steps in almost all drainage design processes are:

- rainfall calculations,
- locating inlets,
- surface runoff calculations,
- design flow calculations,
- canals dimensioning.

Because of the characteristics of the process and many steps that must be made, it is extremely important that all calculations must be quite easy and not time-consuming. Of course, the most important part is still the quality of results which we get in every step.

2.1. Rainfall formulas

The first step in drainage systems design (of course only after we have all the necessary documentation of the given terrain) is calculating rainfall intensity. The main factor influencing rainfall intensity is precipitation frequency (we will use in our calculations). In Poland its value depends mainly on how important the area is where our drainage will be build. In most cases it is taken top-down from the PN-EN 752:2008 standard. In Tab. 1 we can see recommendations from the Polish standard.

<table>
<thead>
<tr>
<th>Drainage standard category</th>
<th>Precipitation frequency</th>
<th>Spillage frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Rural areas</td>
<td>1 a year</td>
<td>1 every 10 years</td>
</tr>
<tr>
<td>II. Residential areas</td>
<td>1 every 2 years</td>
<td>1 every 20 years</td>
</tr>
<tr>
<td>III. City center, service and industrial areas</td>
<td>1 every 5 years</td>
<td>1 every 30 years</td>
</tr>
<tr>
<td>IV. Underground communication facilities and running beneath the streets</td>
<td>1 every 10 years</td>
<td>1 every 50 years</td>
</tr>
</tbody>
</table>

After getting precipitation frequency the rest of the rainfall intensity calculation depends on which method we want to use. There are quite a few formulas that can be used to calculate it. In Poland the most often used is Błaszczyk’s formula (1):

$$ q = \frac{6.631 \sqrt{H^2C}}{t^{2/3}} $$

(1)
As we can see, beside precipitation frequency, Błaszczyk’s formula also uses normal yearly precipitation which is mostly taken from a Climatic Atlas. Values that we can get from these calculations can give us a rough idea about the precipitation variability in a given country. But considering how variant rainfall distribution can be, even on a local (city) scale, it may be not enough. The last parameter used to calculate rainfall intensity with Błaszczyk’s formula is duration of precipitation. This is the value that differs with the chosen method of runoff calculations. In Poland, where mostly the BIM method (2) is used (Weinerowska-Bords, 2010), duration of precipitation means the sum of terrain concentration, channel retention and the time of channel flow (from the beginning of catchment to the considered cross-section). Because of the difficulty in estimating these three components in most cases duration of precipitation is taken as 5, 10 or 15 minutes according to how significant the system is.

### 2.2. Inlet location

Locating inlets is part of the process which is done independently of all other calculations. This is because in most cases this is a task given to road engineers and because of that it is entirely based on variables taken top-down from standards. The main determinant of locating inlets and other drainage equipment is the interval between them. In most situations it is based on the road longitudinal slope. In Tab. 2 we can see an example recommendation (Edel, 2002).

<table>
<thead>
<tr>
<th>Road longitudinal slope i [%]</th>
<th>Maximum interval between inlets L [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 0.8</td>
<td>30</td>
</tr>
<tr>
<td>0.6 ÷ 0.8</td>
<td>15</td>
</tr>
<tr>
<td>0.4 ÷ 0.6</td>
<td>10</td>
</tr>
<tr>
<td>≤ 0.4</td>
<td>8</td>
</tr>
</tbody>
</table>

One of the problems considering the way inlets location is determined is lack of correlation between commonly used guidelines and new technologies which are introduced onto the market. There is no easy way to check if the arrangement of inlets is optimal or if it could be changed in any way.

### 2.3. Design flow

Design flow calculations are based on runoff formulas such as:
- border intensity method (BIM),
- delay coefficient method (DCM).
The DCM method is mainly used in Germany, whereas the BIM method is preferred by Polish designers. Therefore, we will focus on the BIM method (2).

\[ Q = q \times \psi \times F \]

\( Q \) – outflow from catchment \([\text{dm}^3/\text{s}]\),
\( q \) – unit rainfall intensity \([\text{dm}^3/\text{s*ha}]\),
\( \psi \) – catchment runoff coefficient [-],
\( F \) – catchment area \([\text{ha}]\).

As we can see, formula (2) gives us the value of outflow from a catchment, if we are considering the catchment of one inlet that is equivalent to its inflow. This method is particularly easy to use because calculations are based only on rainfall intensity \(q\) which we have from formulas discussed in 2.1, the catchment area \(F\) and just a simple coefficient \(\psi\) that is based on the type of catchment management. The thing that is neglected by formula (2) is the overflow of inlet and the fact that some part of the rainfall flows to farther inlets.

2.4. Rainwater system dimensioning

As we know, sewage systems work with partially filled pipes. It makes all calculations considerably harder than with pressure pipes. Because of that in traditional design designers must rely on nomograms and tables. All dimensioning is based on the design flow calculated for a specific pipe section. Fortunately there are a lot of freeware programs on the market (provided by companies that sell network elements) which are easy to use and give us useful information about the flow parameters.

Taking into account how channel dimensions are determined, we unfortunately have no knowledge at all about the hydraulic parameters of the whole system as one. Each section of the pipe is taken into consideration as an independent part. It becomes a problem when we need to predict how our system will work in special conditions such as small flows or channel overflow.

3. Alternative calculations in drainage systems design

Considering that drainage systems design must be easy and not time-consuming, first of all we should ask the question if more advanced methods and calculations are needed at all. To answer this question let us look at steps discussed in points 2.1 – 2.4.

3.1. Advanced and local rainfall formulas

Even though the rainfall formula presented in point 2.1. is used widely in Poland, it is not very accurate. The main problem is connected with its limited capacity to include rainfall variability across the country and cities in calculations. It is especially important in extreme situations, for example let us compare precipitation in the mountains and at the seaside. The course of the rainfall in these two areas is totally different and should not be described by the same numerical relationship (Weinerowska-Bords, 2010).

An alternative to the traditional approach may be more advanced formulas that not only take into account rainfall duration and frequency, but that are also related to
the part of the country in which the rain occurs. An example of such a method is the one developed by Bogdanowicz and Stachy (1998). It can give us more information about precipitation variability across the country, but it has a few imperfections. According to literature (Kotowski et al., 2010) it can give false results when making calculations for rainfalls of $C = 1$ year frequency.

Considering all the above, the most accurate alternative methods to the traditional approach are local rainfall formulas. An example of such a method is the local rainfall intensity model for Wrocław proposed by Licznar and Łomotowski (2005). This model is used by the city:

$$q_{\text{max}} = \frac{a}{(t + b)^n} + c$$

(3)

$q_{\text{max}}$ – unit rainfall maximum intensity $[\text{dm}^3/\text{s}*\text{ha}]$, 

$t$ – time of precipitation $[\text{min}]$, 

$a, b, c, n$ – regression coefficients, dependent on the probability $p$, acc. to Tab. 3 [-].

<table>
<thead>
<tr>
<th>Probability $p$ %</th>
<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>713.8329</td>
<td>82413.63</td>
<td>643645564</td>
<td>1573.239</td>
</tr>
<tr>
<td>$b$</td>
<td>-3.88429</td>
<td>19.57292</td>
<td>64.88700</td>
<td>4.787518</td>
</tr>
<tr>
<td>$c$</td>
<td>-210.067</td>
<td>20.40978</td>
<td>20.62691</td>
<td>6.351722</td>
</tr>
<tr>
<td>$n$</td>
<td>0.218073</td>
<td>1.752958</td>
<td>3.535880</td>
<td>0.949642</td>
</tr>
</tbody>
</table>

Such methods are widely used across the world, for example, in Germany statistical analyses of rainfall data made it possible to determine local rainfall formulas for the whole country. According to these calculations a precipitation atlas was made (Bartels et al., 1997). It gives really accurate information about rainfall intensity and is really easy to use. This is the direction in which, according to many publications, Polish rainfall intensity calculations should go (Kotowski et al., 2010). One example of progress in this area could be formulas for Gdańsk developed by Weinerowska-Bords.

3.2. Design flow calculations

Methods used in design in Poland (BIM and DCM) give us no information beside the maximum flow value. What we lack to accurately determine how our system should be designed is time distribution of flow, the moment of flow peak, and information about the overlap of flows from different parts of the city or even inlets. They can be obtained using more advanced methods. Two main approaches are:

- hydrological models,
- hydrodynamic models.
On the level of design they are of no real use due to fairly difficult, time consuming calculations and analysis that are needed to define design flow (Kaźmierczak and Kotowski, 2012). On the other hand, they can be successfully used in systems verification and in design of drainage from catchments that have an area of $F > 2 \text{ km}^2$. In such cases we need some more detailed information besides maximum flow. Considering a very wide offer of hydrodynamic models (SWMM, MOUSE, HYKAN, MIKE URBAN etc.) the use of hydrological models is unjustified (Kaźmierczak and Kotowski, 2012) due to their limitations. What hydrodynamic models give us and hydrological do not, is information about drainage surges, water level in channels, and according to that, velocities and energy loss. Most of the hydrodynamic models base on a mathematical description of unsteady flow with the use of Saint-Venant differential equations (4).

Considering all calculations that must be made and the number of variables that need to be defined to use the above methods, it is not recommended to use them while designing local drainage systems. But given the quality of results that we can get, they can be powerful tools not only in case studies but also if we have a more difficult and significant design task to solve.

### 3.3. Advanced pipe dimensioning

Dimensioning is a process of deciding which pipe system from which manufacturer we want to use. According to literature (Brown et al., 1996) the most accurate results can be obtained using pre-defined tables, graphs and formulas given by the manufacturer. This way is the easiest and it is really fast while maintaining the required accuracy.

### 3.4. Inundation models

Inundation models are commonly used in designing and verifying unique and troublesome drainage systems (Hsu et al., 2000). According to Kotowski (2011) there are no easy ways to get information about the interaction between sewage flow and surface flow such as: hydraulic parameters of intakes, water layer on the surface or even when surcharge will occur. Of course in accurate design of more advanced drainage systems this is an integral part of the process.

There are quite a few approaches which can be taken into consideration when talking about inundation models, but for urban areas with high population and dense development the most accurate are 1D sewage flow, and 2D overland surface flow models (Hsu et al., 2000). These models consist of two modules:

- 1D sewage flow (open channel to pressurized),
- 2D surface flow.

The first one, given the nature of the problem: interaction between surface and channels also needs to consider the situation of the surcharge. Saint-Venant equations are most often used here:

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} = S$$

(4)

where $t$ is time, $x$ is distance along the sewers conduit, $U$, $F$, $S$ are vectors.
$U$ (variable vector), $F$ (flux vector) and $S$ (source term vector) may be written as:

$$
U = \begin{pmatrix} A \\ Q \end{pmatrix}, \quad B = \begin{pmatrix} Q \\ Q^2/A + A\bar{p} \end{pmatrix}, \quad S = \begin{pmatrix} 0 \\ gA(S_0 - S_f) \end{pmatrix}
$$

where $A$ is cross-section flow area, $Q$ is flow discharge, $\bar{p}$ is average pressure of water column over the cross-section, $g$ is gravitational acceleration, $S_0$ is slope of channel bottom, $S_f$ is slope of energy line.

Models based on the above equations can describe open channel flow in a sewage. Using for example the Preissmann slot method we can get accurate calculations of flow parameters for transient flow including surcharge situations.

The surface flow problem is usually solved using a 2D diffusive wave model which can calculate (in most situations) accurate results of such parameters as water layer, flow velocities and direction of flow.

Considering all information we can get from such models, they are bound to be an integral part of design and verification processes of more advanced drainage systems. They can give us detailed information about the development of rainfall in an urban catchment. This can be crucial for predicting how our system will work in crisis situations and where its sensitive points are.

4. Conclusion

To sum up, methods used in traditional drainage design are the same irrespective of the type of task that we need to solve. They are the effect of years of practice but are mostly based on formulas that were created a long time ago and are not always accurate nowadays. This is a result of many factors such as: climate changes, better ways of producing components, lower roughness of pipes, development of a new approach to many issues, etc. Given that there is a need to expand knowledge about design, we create new formulas and improve existing ones.

Most important guidelines for developing design techniques come from the characteristics of the design process. In most cases what we need are easy to use and not time-consuming solutions to a problem. This particularly makes it a challenging issue.

In literature we can find a great number of methods giving us accurate results for each step of the design process, but most of them are of no real use due to the limitations mentioned before.

Advanced calculations, on the other hand, can be successfully used in verification of existing systems where we have a lot of data about them and what we need are methods to accurately determine flow conditions. Here the hydrodynamic models of rainwater system, which require only information about the existing system and the rainfall, are the most useful. These can help us to test if what was designed is correct, and if not, what the cause is.

Growing popularity of inundation models makes it easier to predict floods in urban areas. The complexity of calculations is compensated by accurate results showing us where and when we should expect surcharge from sewage and what is causing it. That can be a great help in planning modernization of an existing system or designing a more advanced one.
Concluding, the creation of new calculation methods and improving the existing ones in drainage systems design are two different things. There is urgent need for improving the existing methods so they could be used efficiently with new technologies, but also for developing new methods that will serve to verify existing systems, analyze newly designed ones and possibly evaluate the risk of failures and inundations.

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