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Dissertation thesis: Impact of Land Use and Geomorphological factors on Soil Erosion

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I, Fedorova Darya hereby declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Date:

Darya Fedorova

Aknowledgements

I would like to give thanks to all the persons who became a part of this study:

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To my friends for the moral support.

1. Introduction

One of the most important ecological concerns are the protection, development and use of soil and water resources, including the soil erosion control. Loss of upper layer of soil because of erosion means decreased soil fertility and also, due to the increasing of sedimentation as a result of erosion, the reduced storage capacity in water reservoirs and rivers to carry or collect flood flows. This study deals with the soil erosion processes influenced by surface runoff, geomorphological factors and land use.

Although the research on the basic processes was done before, there is still a need for a new mathematical models to simulate the soil erosion as a dynamic process under different conditions and assumptions. Since the process of soil erosion is complex, a completely theoretical approach is considered to be impractical; a simulated models used the factors that could be controlled or changed by technical or biotechnical techniques.

Furthermore, substantial uncertainty is inherent to all climate change protection. This uncertainty originate from protection changes in temperature and precipitation (natural change) and also from the methods of modelling and scenarios used (e.g. regional or global scenarios). A major tool for the approach to quantify impact of land use and climate change on hydrological processes is their modelling and simulation. There are different models and different scenarios.

The current study was made both on gauged and ungauged basins, presenting different approaches and methods for simulation of overland flow. The development of predictive models required understanding in flow under the soil surface pathways, e.g. process of infiltration, and mathematical representation of the processes.

2. Aim of research

Water security and land protection is a major challenge confronting state governments. Increasing frequency of hydrological extremes, floods and droughts are growing over the last decades. Therefore, there is a need to speed up efforts to enhance efficiency and effectiveness in water resources management to better management of a natural risks and hazards, such as soil erosion. Both basic and applied research bring the result that can be well implemented in land and water policy.

Land use management and changes in land use certainty influence the water regime in a catchment. The processes of man-made impact on the rainfall-runoff relationship through significant land use changes such as urbanization, deforestation or other improper land management can lead to the acceleration of direct runoff and to a lower water holding capacity of the landscape.

The aim of the approach is to mitigate the harmful impact on soil erosion. This means to prepare the methodology which can select the corresponding scenario simulating improvement of water regimes. It is the major aim of this dissertation. The next aims, maybe less substantial, are adequate model choice in order to improve water management processes and design effective biotechnical measures.

3. Theory of Floods and Soil Erosion Control

Soil erosion is one of the forms of soil degradation. Soil is naturally removed by the action of water or wind: such 'background' (or 'geological') soil erosion has been occurring for about 450 million years, since the first land plants formed the first soil. Even before this, natural processes moved loose rock, or regolith, off the Earth's surface. In general, background erosion removes soil at roughly the same rate as soil is formed. But 'accelerated' soil erosion — loss of soil at a much faster rate than it is formed — is a far more recent problem. It is always a result of humankind’s unwise actions, such as overgrazing or unsuitable agriculture practices. These leave the land unprotected and vulnerable (Van Rompaey 2002). Then, during the erosive rainfalls or windstorms, soil may be detached, transported, and (possibly on a long distance) deposited. Accelerated soil erosion by water or wind may affect both agricultural areas and the natural environment. It affects both on-site (at the place where the soil is detached) and off-site (wherever the eroded soil ends up). More recently still, the use of powerful agricultural implements in some parts of the world has led to large amounts of soil move downslope merely under the action of gravity: this process is called ‘tillage erosion’ (Selivanovskaya et al. 2011).

Soil erosion is the process of destruction and demolition of the most fertile upper layer of soil. There are natural and accelerated (anthropogenic) soil erosion factors. Natural erosion is very slow, and during the process, the soil fertility is not reduced. Accelerated soil erosion is caused by unsustainable human activities, which results more active process and enhance the natural erosion (incorrect treatment and irrigation of the soil, excessive application of fertilizers, uncontrolled grazing, deforestation, draining of wetlands, etc.) (Lal 2001).

There are two main types of soil erosion: wind and water erosion. Wind erosion (deflation) is the erosion and deposition of tiny soil particles by the wind. The strongest and most sustained winds turn into the dust (black) storm. In just a few days, they are able to completely demolish the upper fertile layer of soil capacity up to 30 cm (Chepil 1945). Dust storms pollute the waters, the atmosphere, have a negative impact on human health.

Water erosion is the destruction of soil due to the water flow impact. Environmental damage from water erosion is huge. Water draining forms gullies and ravines, washes out of the soil organic and mineral substances. It is the result of rain detaching and transporting vulnerable soil, either directly caused by raindrop splash or indirectly by rill and gully erosion (Poesen 2003).

The form of the erosion development is distinguished on surface (planar) erosion or soil washout; stream erosion - soil scour, and gully erosion. The results of occurring of all these erosion forms can be seen in separate tracts of land, but they often occur together.

Planar (surface) erosion is observed on flat slopes, characterized by steady distribution of the flow. It leads to a steady area of soil erosion. As a result of planar erosion occurs a "cutting off" of the upper fertile layer and shortening of the soil profile.

The intensity of erosion Q can be measured by the loss of weight of the soil m from the area S in time t (Kuznetsov 1996):

$$Q = m/S \cdot t \qquad (1)$$

Torrent erosion occurs when the flow on the slope is redistributed and forms the streams of different intensity, leading to the appearance of gullies and ravines with depth of 0.5-1m. In other words, the stream erosion forms include soil erosion with forming small depressions, which could be eliminated by agricultural tillage (Govers 1996).

Gully erosion is a form of linear erosion when the scours can reach depths of more than 1 meter and if they occur the field can not be agriculturally processed. Unlike stream erosion gullies have their longitudinal profile, different from the profile of the surface to which it is embedded (Valentin 2005).

Depending on the specific appearance of runoff on the soil surface there are three types of erosion: snowmelt water erosion, rainfall erosion and irrigation erosion. Each of these types of erosion can lead to all forms of erosion: planar, stream or gully erosion.

Erosion by melt water is soil washout by waters coming from melting snow. It is characterized by long duration of the process, it covers a large area, but as a rule, it has little intensity, because during the snowmelt most of the time the soil is in the frozen state and can not be washed out (Ollesch 2006).

Rainfall erosion is mostly the soil erosion due to the surface water flow during the rainfall. The duration of its effects on the soil is measured in hours and minutes. The rainfall erosion of soil occurs for two reasons: as a result of washout and scour of the soil by water flowing over the surface and due to the destruction of soil by raindrops. The power of surface soil washout depends on rainfall intensity and duration, as well as the length of the slope and other factors. The damaging effects of rain on the soil are determined by the number of drops, coming at a time, and their size. The larger the drop, the greater speed and greater kinetic energy it has and the more destruction it causes (Wischmeier 1978).

The direct movement of soil by rain is called 'rainsplash erosion' (or just 'splash erosion'). It is an erosion occurring from a direct impact of single raindrop and thus it is effective only when a rainfall has high intensity (Farres 1987). If the intensity is high enough, as the raindrop meets soil by its kinetic energy, it can detach and move the soil particles, though not far away. Because soil cannot be moved far away from the initial hit by raindrop this type of erosion is effective only on site. However, on the steep slopes there can be observed some movement of splashed soil. The rainsplash erosion is only effective in the regions with high rainfall intensity (Abd Elbasit et al. 2011).

The indirect impact of rainfall on soil erosion is the cause of runoff in rills (small channels) or gullies (larger channels). In many countries, rill and gully erosion is the major form of soil erosion (Govers 1992).

Surely not whole amount of precipitations causes soil erosion: vegetation can take away some part of precipitated amount of water; it can be stored in some depressions on the land surface; the significant amount also goes on infiltration process.

The overland flow or surface runoff will occur when the part of rainfall that does not soak into the soil flows down the slope under the action of the gravity force. It could happen for two reasons.

If the rain is torrential, e.g. it arrives quickly with too high intensity to infiltrate, this resulting runoff is called an infiltration excess runoff or Hortonian runoff. Horton (1933) formulated a basic principles for this kind of overland flow: if the interception by vegetation is neglected, surface runoff is that part of rainfall which is not absorbed by soil, i.e. $q = i - f$, where i represents the rainfall and f respectively is infiltration.

Second case is when the rain precipitates on already fully saturated or frozen soil, so that it cannot absorb more. The runoff resulting from this process is called saturation excess runoff.

3.1.The Theory of Floods

Usually floods occur as the result of following causes: snowmelt; quick very intensive rainfall or lighter rainfall, but long-duration; anthropogenic factors, such as failure in the dam system; or it can be a combination of several causes. The flood runoff consists of surface runoff from the land surface when the intensity of rainfall is greater than the infiltration capacity. Rainfall is usually represented by a hyetograph. Recorded rainfall is used to design an actual storm hydrograph. Design rainfall is used for lumped models, as its hyetograph is identical at all points of basin. Data for it could be taken from published information on rainfall intensity-duration-frequency for the whole region (Maidment 1992).

There are four stages during the flood event (Figure 1). The first stage is ‘rainfall’. It initiates the event in the first place. Then comes the ‘rising limb’ stage, that is often quite steep. The rising limb causes most of the erosion as it carries most of the debris and sediment. The flood ‘peak’ is the highest flow rate and average velocity of the stream during a flood event. The ‘recession’ stage is the falling limb of the event but in a natural stream is never as steep as the rising limb due to the floodplains, shallow groundwater, etc.

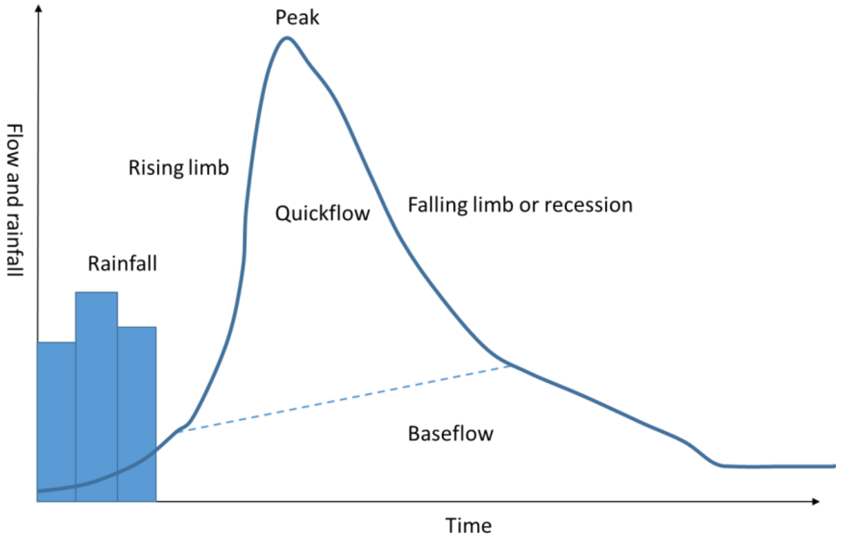

Figure 1. Stages of flood event.

There are processes that prevent some amount of rainfall to become a direct runoff or a rainfall excess. These processes in modelling are considered as losses: interception is the process when the water is kept on vegetation or other surfaces; depression storage is the process when water is held in depressions on ground surface; but the most important loss process is infiltration, when water is going into the surface of soil (Bronsterta and Plateb 1997). There can be also small evapotranspiration during rainfall.

Infiltration affects the shape of hydrograph, the volume of runoff and is considered to be a direct loss.

3.2.Theory of Infiltration

The process of water access into the soil from rainfall, snowmelt or irrigation is called infiltration. Many factors affect the infiltration rate, such as the condition of upper layer of soil or vegetation cover, the properties of soil (porosity and hydraulic conductivity), and the moisture content of soil (Jha 2012).

Soil layers with different physical characteristics can over cover each other, forming the horizons. The infiltration is a very sophisticated process, due to the huge variations in soil properties in space and time and can be only relatively described by mathematical equations (Morin and Benyamini 1977).

The soil profile during the downward transportation of water can be divided on four moisture zones (Figure 2): a near the surface saturated zone, the transmission zone of unsaturated flow, the wetting zone when the moisture reduces with depth, and a wetting front when the sharp disruption between the wetted upper soil and still dry below soil appears (Chow 1964).

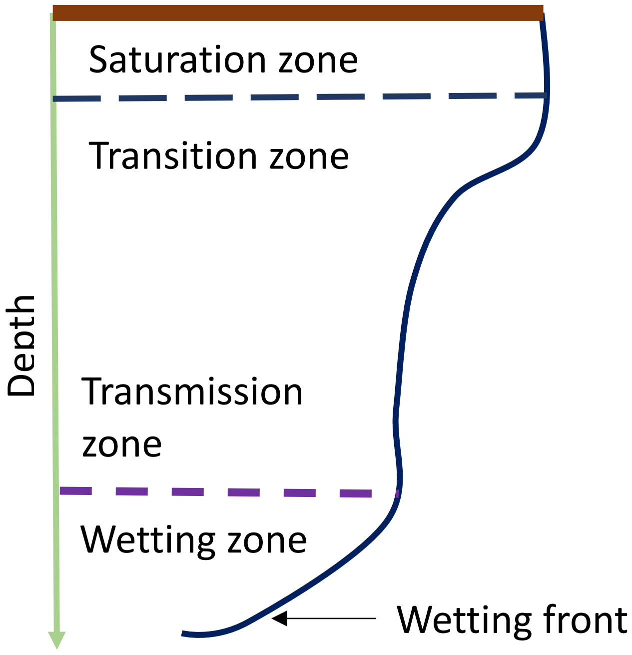

Figure 2. Soil Profile during Infiltration

The rate at which water penetrates the soil is called infiltration rate. The infiltration appears at the potential infiltration rate if the water is ponded in some depressions on the soil surface (Meek et al. 1991).

The most significant subsurface flow processes depending on the direction of water flow are: the infiltration, when water entries the soil and then redistributes to become soil moisture; subsurface flow which is also called unsaturated flow – when the water flows through the soil; and the third process is the soil drainage when water goes from previously saturated upper layer to groundwater. Soil and rocks layers, which enable the water flow, are called porous media. It is a space where the water movement is possible and the maximum volume of it equals to the volume of all pores and voids and is limited by the total capacity of empty space. If all the pores and empty spaces of porous medium are filled by water the flow is saturated; if there is still some air left – the flow is unsaturated (Kutílek 1978). During the process of soil drying out the evapotranspiration occurs, so the soil moisture can be extracted.

3.3.The Flow in Saturated Soils.

The Darcy was the first to notice resemblance between laminar flow in pipes and the water flow through a saturated soil. He made a series of empirical experiments and as a result he found that the velocity of flow was proportional directly to head loss and inversely to the length of flow depth, with a constant factor of proportionality. Later this discovery was identified as Darcy's law (Darcy 1856), which in differential form for steady flow may be expressed as (Eq. 2):

$$q = -K \cdot \frac{dH}{dz} \tag{2}$$

Where q is the Darcy velocity or flux – the flow rate or specific discharge (m/s) per unit cross-sectional area of soil, z (m) is the distance in direction of flow, K is the hydraulic conductivity (m/s). H is the hydraulic head – the energy per unit weight of water. The minus in the Equation 2 stands because the gradient dH/dz in the direction of flow is negative, but the Darcy velocity in that direction is positive (Maidment 1993).

The hydraulic conductivity is the numerical amount estimated by the capability of soil to transfer the water and is determined by the physical characteristics of soil and fluid.

Darcy’s law implements on a homogenous and isotopic saturated soil, when the soil physical characteristics do not vary in space and direction. It can be used for each layer of layered soil separately, but only if each layer does not change the properties with location and direction.

3.4.The Flow in Unsaturated Soils.

The ideal conditions of satured soils could be found in nature rarely, though the saturation may occur in some particular layers or on at the certain depths for short periods of time. Usually, both the water and air can be found in soil pores, so the water flows in unsaturated soils. Unsaturated soil zone is connecting the saturated zone of groundwater with the soil surface. With the accumulation and transportation of water, other nutrients and elements are transported and stored too. The accumulation of water and nutrients in this zone of soil can be essential for the existence of the biosphere (Lal et. Shukla 2004). In theory, the unsaturated flow is driven by the contemporary flow of two fluids that cannot be mixed – air and water. The unsaturated flow is based essentially on the same laws as flow in saturated soil. However, unlike the saturated flow, the empty spaces in soil horizons are not fully occupied by water, as it was already mentioned previously, and thus some of the pores and voids are filled by air and during water penetration the soil can absorb more water or, in reverse, to drain (Kutilek et al. 2004). It is assumed that air can easily release as the water goes in, so it gives the insignificant resistance to water flow, but sometimes there are situations when air cannot go out before the water infiltration, or even if it can the resistance to water flow can be quite significant (Maidment 1992).

The Darcy law for unsaturated flow was modified by Buckingham (Buckingham 1907) by simplifying the hudraulic conductivity and the soil water potential. He described the hydraulic conductivity *K* through the function of the volumetric soil water content *θ*: *K* = *K(θ)* – the capillary conductivity. The K in the function became an unsaturated hydraulic conductivity. He also described the soil water potential h as a h = *h(θ)*- the soil water matric potential head, and suggested that in unsatured flow it is negative. The Darcy-Buckingham equation for unsaturated flow can be expressed by (Eq. 3):

$$q = -K(\theta)\left[\frac{\partial h(\theta)}{\partial z} - 1\right] \tag{3}$$

Where *z* is the soil downward depth.

The Figure 1 represents the explanation of the processes. If the given cube is the ideal cube of saturated soil it can be assumed that the difference of all inflow in the element and the outflow from it equals the difference in the water content of the element at a time Δt. It is valid only in case of incompressibility of water deforming the soil and when the viscosity or conductivity do not depend on the position (Kutílek 1978, Kovář et al. 2008).

If the unsaturated flow of water is assumed as a theoretically incompressible liquid in the homogenous isotropic environment without free level. In the Cartesian coordinates system (x, y, z) with the bottom lengths X, Y and height Z, the X side of the cube is parallel to the *x* axis (Figure 3). According to the conditions of unsaturated water flow in a homogenous isotropic environment the function of the flow velocity *v(x)* is defined in the direction of *x* axis. The difference of the flow rate is continuous.

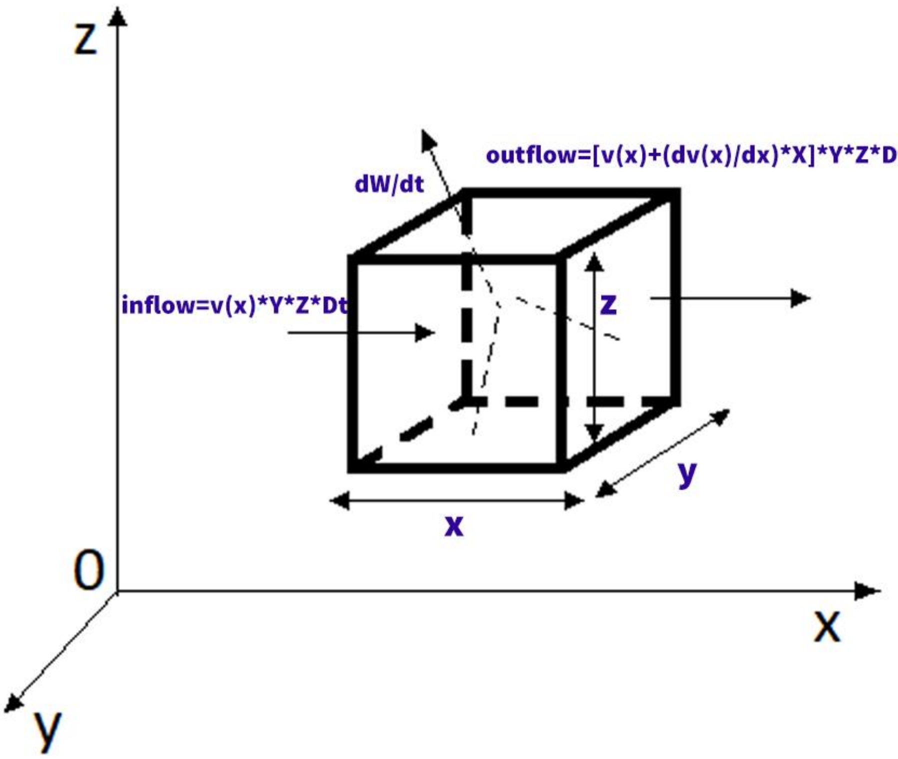

Figure 3. Graphic representation of inflow and outflow processes for the unsaturated flow (Kovář 2010).

The amount of water at the inlet to the cube in the direction of *x* axis and for a certain time duration Dt can be expressed by Equation 4:

$$Inflow \ = \ v(x) \cdot Y \cdot Z \cdot Dt \tag{4}$$

Expressing the increase in flow velocity *v(x)* on the outflow from the cube by the differential expression: *v(x) + (dv(x)/dx)·X,* the amount of water on the cube outlet in the direction of *x* axis could be described as (Eq. 5):

$$Outflow \ = \ [v(x) + \frac{dv(x)}{dx} \cdot X] \cdot Y \cdot Z \cdot Dt \tag{5}$$

The difference in the amount of water in the inlet and outlet of the cube *(X,Y,Z)* for the certain time *Dt* equals the difference in moisture content *W* in the time *t (dW/dt)* in the same cube for the time period *Dt*. This statement can be expressed by Equation 6:

$$Inflow - outflow = \frac{dW}{dt} X \cdot Y \cdot Z \cdot Dt \qquad (6)$$

If we describe the inflow and outflow through the Equations 5 and 6, as the result Equation 7 has the following form:

$$-\frac{dv(x)}{dx} = \frac{dW}{dt} \qquad (7)$$

The relation 7 represents the continuity equation for the unsaturated flow in the *x* axis direction. It can be also derived for the direction of axis *y* and *z*. For the previously described Cartesian coordinates system *(x, y, z)* would be valid following Equation 8:

$$-\left[\frac{dv(x)}{dx} + \frac{dv(y)}{dy} + \frac{dv(z)}{dz}\right] = \frac{dW}{dt} \qquad (8)$$

With application of Darcy-Buckingham law (Buckingham 1907, Kutílek et Nielsen 1994) for the Equation 8 for the unsaturated flow the flow velocity *v(x)* in the direction of *x* axis can be expressed through the potential gradient *G (dG/dx)*. The vector *grad G = dG/dx* here represents the gradient of the given skalar potential G in the direction of *x* axis (Eq.9):

$$v(x) = -k(N) \cdot grad \cdot G = -k(N) \cdot \frac{dG}{dx} \qquad (9)$$

For the simplification the relation above could be expressed through the potential *G(M)* in the unsaturated porous medium without free level: *G = z + N*, where *z(M)* is the geodetic height above the reference plane and *N(M)* represents the suction (negative) pressure. Parameter *k(N)* presents the unsaturated hydraulic conductivity, which depends on the suction pressure *N* and on the moisture content W (Toman et al. 1993, Kovář 2010).

Infiltration is the vertical flow through the topographic surface to the soil and the velocity of it is called the rate of infiltration *v*. The total amount of infiltrated water is called the cumulated infiltration *I* (Kutílek et al. 1993).

3.5.Richards equation.

The occurrence of the steady flow in nature is rather exceptional with the prevalence of the unsteady flow. For the study of unsteady flow besides the velocity of flow should be also considered the difference in the water content in soil, e.g. in the pores. The processes of emptying or filling of pores are described by the continuity equation as the difference in moisture content at a certain time (Kutílek 1978).

The modelling of water movement in an unsaturated porous environment has been carried out for over 80 years using the Richards equation (Richards 1931). It contains the continuity equation and the Darcy-Buckingham relation. The Richards equation is widely used by hydrologists, although the obtaining precise input parameters can be problematic. It is based on the dependence of the hydraulic conductivity K and the matrix potential h on the moisture content T (also called the retention curve). Measuring both dependencies is not an easy task, the value k can change in thousands of times with the change of moisture from minimum to maximum.The solution is highly sensitive (Vogel et al 1988).

With the adding the Equation 9 to the continuity Equation 7 the one-dimensional unsaturated flow in *x* axis direction is obtained (Eq.10):

$$\frac{d[k(N)\cdot\left(\frac{dG}{dx}\right)]}{dx} = \frac{dW}{dt} \tag{10}$$

The unsaturated flow in the direction of y and z axis can be obtained using the same process, so for the Cartesian coordinates system *(x, y, z)* can be derived the following Equation 11:

$$\frac{d[k(N)\cdot\left(\frac{dG}{dx}\right)}{dx} + \frac{d[k(N)\cdot\left(\frac{dG}{dy}\right)}{dy} + \frac{d[k(N)\cdot\left(\frac{dG}{dz}\right)}{dz} = \frac{dW}{dt} \tag{11}$$

It can be also expressed by the scalar Hamilton operator nabla ∇ (Rektorys 1995):

$$\nabla[k(N)\nabla G] = \frac{dW}{dt} \tag{12}$$

The one-dimensional unsaturated flow in *x* axis direction described by Eq.10 can be axpressed by relation $G = z + N$, then $(dG/dx) = (dN/dx)$ can be defined as Equation 13:

$$\frac{d[k(N)\cdot\left(\frac{dN}{dx}\right)}{dx} = \frac{dW}{dt} \tag{13}$$

The same approach can be used to describe the unsaturated flow in the direction of y axis, for z axis direction the left side would be extended on $(dk(N)/dz)$:

$$\frac{d\left[k(N)\cdot\left(\frac{dN}{dx}\right)\right]}{dz} + \frac{dk(N)}{dz} = \frac{dW}{dt} \tag{14}$$

For the Cartesian coordinates system (x, y, z) in the homogenous porous environment for the unsaturated flow without free level can be derived the following Equation 15:

$$\frac{d\left[k(N)\cdot\left(\frac{dN}{dx}\right)\right]}{dx} + \frac{\left[k(N)\cdot\left(\frac{dN}{dy}\right)\right]}{dy} + \frac{\left[k(N)\cdot\left(\frac{dN}{dz}\right)\right]}{dz} + \frac{dk(N)}{dz} = \frac{dW}{dt} \tag{15}$$

With the addition of nabla operator the Eq 15 can be expressed as:

$$\nabla \cdot [k(N)\nabla N] + \frac{dk(N)}{dz} = \frac{dW}{dt} \tag{16}$$

Those equations 10-16 are named Richards equations by the name of author who expressed them first (Richards 1931, Toman et al 1993, Kovář 2010).

3.6.Philip's equation

Using the Richards equation either to describe the soil moisture distribution or to analyze the drainage processes, occurs the problem when soil moisture content *W* is highly dependent on suction pressure *N*. One of the solutions for the homogenous soils with the stable primary distribution of water in soil is the Philip's equation (Philip 1957). The equation provides a solution for vertical infiltration into a nonlayered soil. The expression dW/dt in Richards equation could be written as $dW/dt = (dW/dN)\cdot(dN/dt)$. By adding the so-called specific or differential water capacity indicator $Cw(N)$, where $Cw(N) = dW/dN$, the Richards equation could be expressed in so-called capacity form (Eq. 17):

$$\frac{d\left[k(N)\cdot\left(\frac{dN}{dz}\right)\right]}{dz} + \frac{dk(N)}{dz} = Cw(N)\frac{dN}{dt} \qquad (17)$$

Those techniques and methods are used to reduce the number of variables for analytical and numerical solution of Richards equations (Kutílek 1975, Kutílek et Nielsen 1994). Philip's description of vertical infiltration is based on the perturbation method and is made from the Richards equation type (7), which transforms to diffusion type, when the impact of gravity is neglected and the equation then is solved through the Boltzman transformation. The result of solution is the cumulative infiltration $i(t)$ $[L]$ in the time period $t[T]$ expressed as an infinite series (Eq. 18):

$$i(t) = \sum_n C_n \cdot t^{n/2} + k(k_i) \cdot t \qquad (18)$$

Where C_n $[L, T]$ is mathematically and physically derived n-th member of series, t $[T]$ is time, $k(k_i)$ $[L\cdot T^{-1}]$ is the unsaturated hydraulic conductivity for the initial moisture distribution Q_i, L and T is the length and time unit. If the last member of the equation 18 is neglected and substitute $n = 2$ then equation 18 gets the form of a Philip's cumulative infiltration two-parameter equation:

$$i(t) = C_1 \cdot t^{1/2} + C_2 \cdot t \qquad (19)$$

The $C_1[L\cdot T^{-1/2}]$ parameter represents the soil sorption properties and the parameter $C_2[L\cdot T^{-1}]$ represents the long-term infiltration. The $n = 2$ approximation is proved to be suitable for either water management and scientific purposes.

Usually the Equation 19 is expressed through the sorptivity S $[L\cdot T^{-1/2}]$ and the long-term infiltration coefficient A $[L\cdot T^{-1}]$:

$$i(t) = S \cdot t^{1/2} + A \cdot t \qquad (20)$$

The equation of infiltration intensity $v(t)[L\cdot T^{-1}]$ can be obtained by derivation of cumulative infiltration $i(t)$ $[L]$ for time t, then the following expression is valid: $v(t) = \frac{di(t)}{dt}$. The simplified form of result is the Equation 21:

$$v(t) = \frac{1}{2}S \cdot t^{-1/2} + A \tag{21}$$

If the t time period is large, the infiltration rate becomes a constant, and equals to the saturated hydraulic conductivity K_s (Maidment 1992). The last equations 20 and 21 were used to evaluate the direct field experimental infiltration testing. The use of these equations, which appropriately approximate the real natural infiltration processes to the unsaturated porous environment, has been verified many times in both science and engineering (Toman et al. 1993, Kovář 2010).

4. Hydrological models

The main purpose of any modelling is to get information about the object which should be modelled, simulated or replaced from the quasi-object – the replacement or model. The aims of model depend on the chosen properties important for study; the model should imitate the selected aspects of interest (Singh 1988). The model should also be similar, but not exactly identical, a working simulation of the real object. The closer the results of model to real system, the better is the model. Also best model should require less parameters and be as simple as possible. The modelling is usually used if the system or object is complex to allow the possibility to predict the behavior of real object. Often the sophisticated system is divided on several simpler or at least more tractable models. Some details of the real object can be neglected for their insignificance for current study of if they are too complicated and difficult to manage. (Dooge, 1973).

The mathematical modelling of hydrological processes is, in some sense, every use of the mathematical equations, relations or formulas to describe the natural characteristics of hydrological processes or even whole systems. Every time when mathematical equations are used to represent the relations between variables or to simulate the structure of a single variable can be called mathematical modelling. There is no hydrological process that could not be described through the mathematical view, the modelling of hydrological processes includes analysis of timeseries and stochastic modelling.

As in any other scientific field, the development of personal computers provoked the sudden jump in the mathematical modelling. The availability of computers, new user-friendly operational systems and different application software allows hydrologists to accomplish the sophisticated calculations that use lots of different data. The mathematical modelling have become an important part of the any hydrological management, predictions and control systems and in providing the hydrological forecasts.

A runoff model is generally as a set of equations that allows to simulate or model a runoff as a function of different parameters which describe catchment characteristics. Usually the most important inputs, used for all hydrological models, are rainfall data and the area of catchment. Depending on the type of model and data availability, other watershed characteristics such as soil properties, type of vegetation cover, landscape topography, etc. could also be necessary.

There are several approaches in order to classify hydrological mathematical models (Jajarmizadeh et al. 2012).

According to Chow et al. (1988) hydrological models can be classified into two types: abstract (mathematical) models and physical models (Figure 4). Physical models are divided into two categories too: analog models and scale models. A scale model is the diminished model of a real hydrological system, while the analog model is used when the physical system has the similar properties with the first example.

Abstract or mathematical models express all processes in the form of mathematical formalisms. The core of model is the set of equations; it is operated with input and output data. Different types of variables are used: for example, the space and time representing set of variables, probabilistic or random variables.

The abstract models can be also divided into two subclasses: stochastic and deterministic models. A deterministic model simulates only with a given input data for all time and calculates similar output, e.g. it does not have randomness. However, the partial randomness in outputs could be created by stochastic models (Chow 1964).

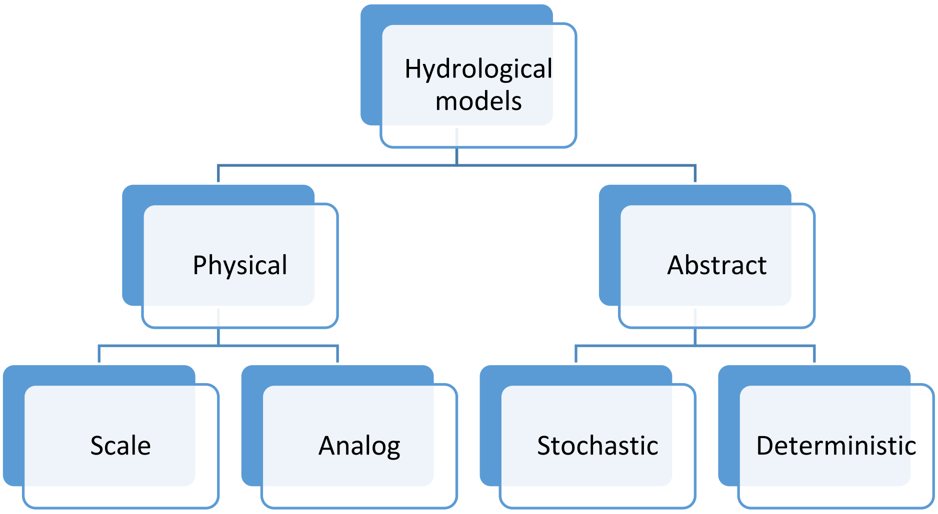

Figure 4. Classification of hydrological models according to Chow.

The classification which is used in WMO guides (2009) for hydrology engineers is partially based on the categorization originally proposed by Lewarne (2009). He divided all hydrological models into five groups by the definition of mathematical models and put in his classification polar conditions.

A model can be static or dynamic, for example. Dynamic models include time as an independent variable in the quantitative relationship between values of two variables, for example, the river flow in a given time in some particular cross-section point and a series of earlier rainfall data in the given catchment: rainfall-runoff models. Static models exclude time. Commonly, dynamic models are developed in the forms of differential equations (Singh 1988, Viessman and Lewis, 2008).

Another category divides models on the linear and non-linear types. Linear models use simple correlations between input and output data, obey the superposition principle, and are more comfortable to use, while the non-linear models are more difficult, due to the irreversibility.

Third class of models matches the deterministic and probabilistic (stochastic) models.

Category four divides models on lumped and distributed, it is based on the parameters role. Lumped models are used for the unvarying states in a hydrological system in contemporary with distributed models, which indicate the diversity in states throughout the system. Due to the simplification of processes, lumped models are considered more helpful in most cases, though it should be noted that the choice between lumped and distributed models depend on the degree of necessary accuracy in properties of modelled watersheds (Refsgaard and Abbott 1996, Beven 1996).

The last category describes the physically-based and conceptual models. The physical model is mathematical representation of the real hydrological processes. It is somehow idealized mechanistic model, the hydrological processes are described by finite difference equations. It requires the huge number of physical characteristics of basin, such as initial water depth, soil properties, topography, etc., however it does not need long series of hydro-meteorological data (Abbott et al. 1986). A conceptual or parametric model simulates the real hydrological processes using two related approaches: logical and physical. In this type of hydrological models the semi empirical equations are normally used and the parameters of model are determined not only from field measured data but also through calibration. For the calibration, long series of hydrological and meteorological data records are required.

The classification by polar definitions is showed on Figure 5.

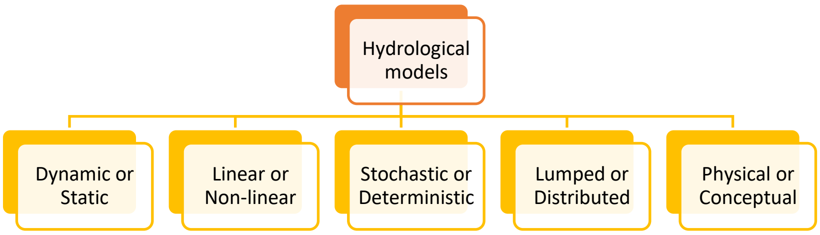

Figure 5. The polar definitions classification

In order to simplify the classification, Gosain et al (2009) mentioned that such a broad classifications arrived from the early attempts in hydrological modelling and nowadays major amount of models can be divided on three main groups: black-box models, conceptual (grey-box) models and deterministic, but of course there can be also subclasses inside each category (Figure 6).

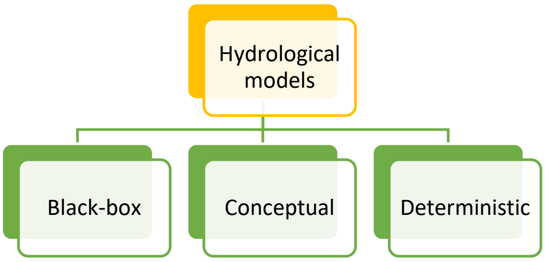

Figure 6. Classification of hydrological models according to Gosain.

The black-box models mentioned above are the purely empirical models, they do not attempt to model the internal structure, but find the best solution to match the input and output of the hydrological process.

Deterministic models are complex physical models and require a large amount of data and computational time, however they demonstrate the internal view on the hydrological process which helps to understand the hydrological system better. In the deterministic model each variable is represented by the single value and the interrelations between variables and parameters are determined. The purpose of deterministic models is to describe the physical processes by mathematic formalisms. The more precise is the model, the more input data it would need. The classification of deterministic models widely used in different water management organizations in Czech Republic was made by Kovar (1990). The deterministic models according to the given classification are divided on two classes: hydrological or parametrical models and hydrodynamic models (Figure 7). The hydrodynamic models are based on complex theoretical concepts and physical laws that rule hydrological system. They are formulated on spatial distribution and evaluation of parameters of physical characteristics and require data on initial state of model and morphology of catchment. The physically based models can reduce the defects of the other types of models because of the manipulation with physically interpreted parameters.

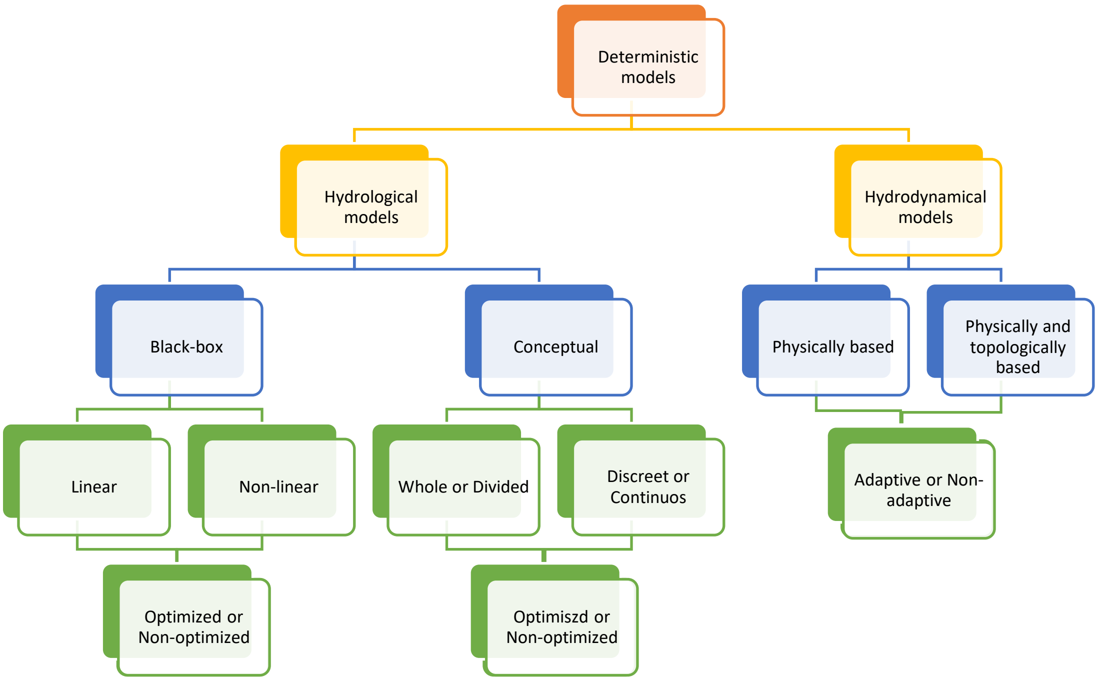

Figure 7. Classification of deterministic models by Kovar.

Unit Hydrograph Concept

The Unit Hydrograph (originally named unit-graph) first proposed by Sherman (1932), is a direct runoff hydrograph coming from 1 cm of excess rainfall emerged over the runoff area at a constant rate for a given time duration. Sherman distinguished the surface runoff and groundwater flow and advised the Unit Hydrograph (UH) method to estimate only surface runoff. However, originally the term “unit” was related mostly to the unit of time, but later it has been understood as a unit of precipitations amount. The simplification of UH theory is a linear model for computing the hydrograph generated from any amount of rainfall excess. The basis of the UH method is formed by the main principles and conditions of linear system analysis (Chow et al.1988).

5. Hydrological Extremes

Nowadays, due to the significant changes in climate and land use the hydrological extremes – floods and droughts – became a serious threat to economy, human welfare and even life. Floods and droughts are the result of a various processes at different space- and time scales: physical processes in the atmosphere, in the catchments, in the river systems, and different types of human activities, which feedback, in turn, on physical processes.

5.1.Erosion and soil

In prehistoric times, the development of erosion was determined only by natural factors. With the development of human activities and the development of new areas of arable lands, soil erosion has increased substantially and has become dependent mainly on land use. Modern erosion usually appears as the result of combination of two groups of factors. Natural factors create conditions for the occurrence of the erosion and improper human activity is a major cause of deflation and water erosion.

The development of water erosion on a particular territory is determined by natural and anthropogenic factors (Figure 8), such as climate, topography, vegetation, wildlife, soil properties and human activities.

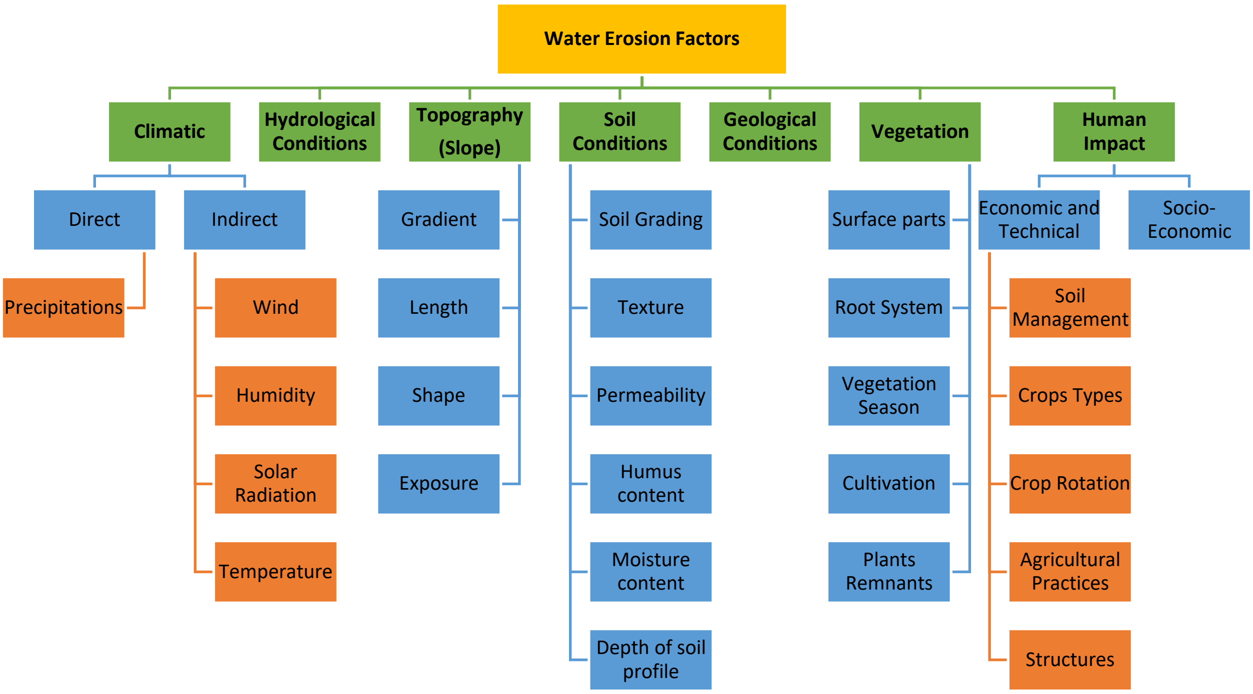

Figure 8. The factors of water erosion.

The whole soil erosion process has three stages. At first, the soil particles are detached from soil surface. Second stage is the transportation of these particles. The last phase is the deposit of soil material which occurs when the energy for further movement decreases (Boardman et al. 2009).

The rate of erosion depends not only on the external factors, but also on the properties of the soil, the capacity of soil to resist erosion. This ability is called soil erosion resistance and is the reciprocal of erodibility: the higher the resistance of soil erosion control, the lower the rate of erosion.

The soil stability depends on many soil properties, but primarily on the particle size distribution. Soils, different in particle size distribution, are exposed to erosion at different flow rates, i.e., the critical flow rate (minimum speed at which the particles begin to detach from the soil) for different soil varies. The degree of increase of the flow eroding ability with increase of its speed for different soils is different too. The lowest critical speed is for the dust soils particles (size of 0.001-0.05 mm).

The direct impact of the granulometric composition on soil erosion resistance should lead to an increase in erosion with decreasing of particle size, since the surface area of particles experiencing the side water pressure is on the increase (van Tol et al. 2011). In fact, there is an opposite pattern: with an increase in the particle size, the soil erosion resistance generally decreases. This is because the erosion depends not only on size of the particles but mostly on bond strength between the particles and the filtration capacity of the soil. The more particles are linked and the higher the water-stable aggregates, the bigger is soil erosion resistance.

The filtration capacity of the soils of different particle size varies. In sandy soils, it is many times higher than that of non-structured clay and loamy soils. However, in the case where the clay soil is well treated, they acquire a good water-resistant structure and relatively high filtration capacity. In general, light soils are usually more prone to erosion, especially the intensive development on these soils have different forms of gully erosion: gullies, ravines, ruts. The erosion resistance of soil increases with increasing of humus content, since it depends on the degree of soil structuration (Lane and Kidwell 2003).

The soil resistance to erosion is highly dependent on soil structure. The fine-grained structure soils have the filtration capacity 10-30 times higher than non-structured soils and are characterized many times greater erosion resistance. However, aggregate and soil texture are interrelated, that is, the structure of the soil depends on the particle size distribution (Knapen 2007).

In the SCS CN method the soil properties are represented by a hydrological parameter: the minimum rate of infiltration obtained for a bare soil after prolonged wetting. The influence of both the soil’s surface condition, presented by infiltration rate, and its horizon, presented by transmission rate, are thereby included. The parameter indicating the soil’s runoff potential is the basic qualitative parameter of the classification of all soils into four groups (Table 1):

Table 1. The Hydrological Soil Groups (defined by SCS).

Group A	Soils having high infiltration rates even when thoroughly wetted and a high rate of water transmission. Example: deep, well to excessively drained sands or gravels.
Group B	Soils having moderate infiltration rates when thoroughly wetted and a moderate rate of water transmission. Example: moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse structures.
Group C	Soils having low infiltration rates when thoroughly wetted and a low rate of water transmission. Example: soils with a layer that impedes the downward movement of water or soils of moderately fine to fine texture.
Group D	Soils having very low infiltration rates when thoroughly wetted and a very low rate of water transmission. Example: clay soils with a high swelling potential, soils with a permanently high watertable, soils with a clay pan or clay layer at or near the surface, or shallow soils over nearly impervious material.

The presence of soluble salts in the soil also reduces the soil erosion resistance. During draining off soils salts deposits out of solution in the form of crystals, joined by a large number of water molecules, and loosen the soil mass by pushing the particles of soil. When rain falls, salt dissolve, the surface layer becomes loose, unstable state.

On the soil erosion resistance also affects the soil moisture. Dry soils have a more solid structure than wet. Therefore, the repeated rainfall is more erosionly dangerous than the first storm. The strength of its effect increases more due to the fact that moist soils are less able to absorb and retain moisture and cause a more intense discharge. In the CN method this condition was classified in three Antecedent Moisture Condition Classes Table 2:

Table 2. The classification of soil by AMC

AMC I	The soils in the drainage basin are practically dry
AMC II	Average condition
AMC III	The soils in the drainage basin are practically saturated from antecedent rainfalls

Erosion appears in various parts of the world in different ways. The most relevant climatic characteristic for the erosion formation is the rainfall (Table 3). The big influence on soil erosion also has precipitation patterns. The same volume of rainfall, but in a shorter time increases erosion. On the intensity of erosion greatly affects the size of raindrops, which depends on the intensity of the rain. The diameter of the raindrops for the long-duration rains is 1-1.5 mm, for the storm it is 3-5 mm. The weight of these storm raindrops is 5-15 times bigger, and the speed in the atmospheric boundary layer is 2 times faster. Consequently, the force of the impact of torrential rainfall drops is 10-30 times greater than of the long-duration rain (Zakharov 2009).

Table 3. The relation between the runoff and soil loss and the intensity of rain

Rain intensity, mm/min	**Runoff, in % of precipitations volume**	**Soil loss, t/he**
0,25	5	0,22
0,5	19	0,75
1	56	6,6
2	61	35

5.2.Surface runoff and water erosion

As was mentioned before, the overland flow or surface runoff is the flow of water that occurs when the part of rainfall that does not infiltrate into the soil flows down the slope under the gravity force. The size and speed of surface runoff and thus the rate of soil destruction and erodibility largely depends on the topography characteristics; the intensity of erosion or the amount of material washed off for the same time, increases with the flow velocity. The low speeds of flow has no significant damaging effects on soils. The erosion in this case is insignificant. The rate of flow of water, at which begins its destructive effect on the soil, called the critical velocity. The critical velocity for moving the soil particles varies depending on their size.

Various landscape characteristics have different effects on the flow rate and intensity of erosion. The greatest influence on the flow rate has a slope angle, with the increase of which sharply increases the flow rate. Slope angle of medium and steep slopes is usually expressed in degrees. Depending on the angle, slopes can be divided into flat, slightly sloping, highly sloping, steep and very steep (Sprenger 1978). In flat areas the surface angles are small: less than 1 °, on the acclivous slopes - 1-2°, declivous - 2-5°, steep - 5-10°. The slopes with angle more than 10 °, are considered very steep. Such slopes cannot be used in agriculture without special ameliorative measures.

Erosion processes are directly related to the steepness of the slopes. The slope angle primarily determines the soil erosion (Table 4).

Table 4. The extent of erosion of soil, depending on the steepness of the slope

Slope characteristics	**Slope angle, °**	**Possible rate of soil erosion**
Flat area	< 1	No erosion
Slightly sloping	1-2	Small
Highly sloping	2-5	Medium
Steep slope	5-10	High
Very steep	>10	Very high

Not only the steepness of slope effects the surface runoff but also its length. At great length the lower part of the slope gets more surface water than the upper and middle parts so, the soil in the bottom parts of the long slope is eroded much more than soil on the short length slopes with the same angle of steepness. This is how appears the gully erosion, landslides and landfalls in the lower parts of the hilly territories and intermountain depressions slopes.

The intensity of the erosion due to the length of the slope is particularly higher in the mountainous areas, where the valleys are characterized by long slopes (Graiss and Krautzer 2011). Even with average rainfall intensity (20-30 mm per day) due to surface runoff on a long slope its lower part receives a large amount of water, which results the disastrous consequences (Feiznia 2011). Small rivers after medium intensity rainfall lasting more than one day turn into a huge swirling muddy streams, which wash away the soil from the banks, the uprooted trees and bushes and flood the streets of villages and towns (Gyssels 2005).

The reason for these phenomena in mountainous areas is that on long slopes there are large catchment areas from which the valleys receive huge masses of water. In the plain areas, on the short slopes so large basins could not form, so the lower parts of slopes accumulate much less water (Zhang et al. 2011).

The length of the slopes determines the size of the catchment area and the area from which the fine soil particles are demolished, and the amount of sediment coming to river course. At the same slope gradient with increasing of catchment area the amount of incoming material increases too (Khitrov et al. 2007).

Flow velocity depends not only on the steepness of the slope, but also on other factors - the surface roughness, thickness of the flowing water layer, and others. Roughness coefficient is the value which is difficult to measure, so usually the known approximate values are applied (Govers et al. 2000).

On the intensity of erosion affects also the shape of the slopes. This is due to the generation of a stable erosion profile forms by the erosion processes. Stable erosion profiles have a concave sectional shape, and its base is on the plane of erosion basis. The convex profile slopes experience more severe erosive effect, because they are more far away from a steady erosion profile.

Demolition of soils is not unlimited. The maximum depth of erosional incision can not be lower a certain level - the erosion basis (Skryabina 2012).

The erosion basis is the horizontal surface, at level of which the erosion stops, i.e. the surface runoff water do not fall below this level. The erosion basis coincides with the level of the water surface of the water inlet located in the lower part of the slope, or some cavities which are not filled with water. These depressions are often found in dry areas.

The intensity of erosion depends also on slope exposure, which affects on the rate of erosion, due to the fact that the slopes of different exposures receive different amounts of solar heat.

As a result, there are differences in humidity, thermal conditions, have different amplitude of temperature fluctuations, different speeds of wind and different composition of natural vegetation. All these factors lead to differences in the rate of soil erosion, which in the northern hemisphere is usually higher on the southern slopes. The most severely affects on soil erosion by the exposure of slopes occurs in the spring time. In the spring on the southern slopes the snow melts faster and melt waters moves on thawed bare soil, causing erosion. Soil northern slopes at this time are in a frozen state, covered with snow and are not a subject to erosion. Also on the intensity of erosion affects the type of watershed.

5.3.Erosion and Flood Control Measures

Erosion control is a full set of different actions intended at lowering the intensity of erosion to a relatively relevant rate and limiting the development of damaging erosion.

There are three main types of erosion control measures: biological, technical and cultural (Figure 9). Biological measures include all types of planting and are based on erosion-control abilities of vegetation cover. Technical practices include adjustments on landscape and different land protection and water flow controlling constructions. The cultural measures are mostly agricultural and soil cultivation practices. The effective soil erosion control actions usually contain all three types of measures.

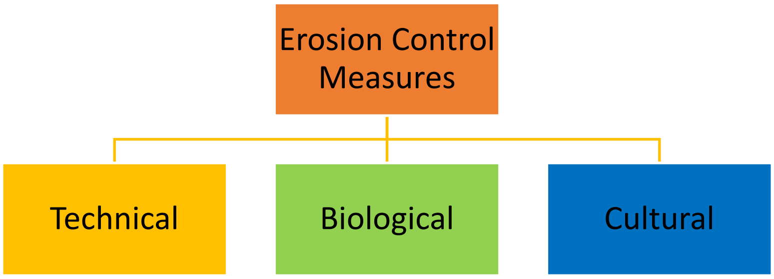

Figure 9. Erosion control measures.

To efficiently protect soil and water resources it is necessary to know the factors affecting these resources and measures for controlling those influences to conserve the resources. The long series of data, many years of observations on field, plot and small watersheds provided the information on the complex relations involved in the nature processes and especially, on the influence of human activity, such as land use and farming. These studies became the base for the Universal Soil Loss Equation (USLE) which is considered to be a good controlling and planning tool. It has been displayed to do a good work of estimating erosion for many disturbed-land uses. The USLE was developed from the research information in combination with additional data of empirical experiments and physically-based principles. The process of developing began Bennet (Helms, 2008), who was one of the most respected soil scientists in US, back in 30s. Later his studies were used by US SCS to form an USLE. It has now been around 60 years since the first release of erosion prediction method.

The Universal Soil Loss Equation (USLE) is (22):

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{22}$$

Where A is the computed soil loss per unit area, expressed in the units selected for K and for the period selected for R; R, the rainfall and runoff factor, is the number of rainfall erosion index units, plus a factor for runoff from snowmelt or applied water where such runoff is significant; K, the soil erodibility factor, is the soil loss rate per rainfall erosion index unit for the specified soil; L and S are the slope length and steepness factors in relation to the conditions on a unit plot; C, the cover and management factor, is the ratio of soil loss from an area with specified cover and management to that from an identical area under the tilled conditions (C thus ranges from a value of zero for completely non-erodible conditions, to a value of 1.0 for the worst-case); and P, the support practice factor, is the ratio of soil loss with a support practice like contouring, stripcropping, or terracing to that with straight-row farming up and down slope.

The rainfall, soil erodibility and other terms used in the USLE have evolved over the years from data derived for various conditions, which later resulted in RUSLE (Revised Universal Soil Loss Equation) due to the need to replace the USLE with a physically-based model and to computerize and update the USLE.

The USLE equation was used to evaluate the extent of erosion in Czech Republic by many researchers. One of the studies was made by the Šarapatka and Netopil (2010). Processing the input data from the studied area was simplified by using geoinformatic methods. Commonly available commercial ArcGIS software was used for a GIS model of potential erosion.

Soil and water are interrelated; methods that control and protect water on slopes also conserve the soil and control erosion. The different types of runoff management may be classified on three groups: increase water intake and storage and so reduce runoff; control the surface runoff; dispose safely of the excess rainfall as runoff or concentrate the torrential rainfall runoff.

In general, runoff is decreased by increasing the infiltration of rainwater into the soil through biological conservation measures. Where this cannot be done, land works (physical control measures) can provide soil surface protection by keeping water to give it time to infiltrate. Such physical protection methods include land shaping, the construction of contour bunds, terraces and ridges (Comino et al. 2011, Widomski 2011). It requires some engineering, considerable technical design, supervision, proper construction and maintenance. In contrast, the biological methods include some soil management and agronomic cultural practices such as appropriate land use and preparation, fertility maintenance, crop residue management, the use of cover crops (Bucur et al. 2011).

The vegetation of all kinds is a powerful factor in erosion control. The degree of influence of vegetation depends on the type and condition of vegetation: the better it is developed the greater its role in regulation of surface runoff and soil erosion control. The role of vegetation in erosion control is in the reduction of the impact force of raindrops, and therefore vegetation prevents the destruction of soil aggregates, as most of the rain drops fall at first on surface of the plant and then flows down to the soil (Vásquez-Méndez 2011). Some amount of precipitation is caught in the aerial part of the plant and it does not reach the ground, and therefore does not participate in the formation of surface runoff. In natural plant communities the soil surface is covered with a layer of semi-decomposed litterfall (Rodriguez-Caballero 2012). It has good permeability and moisture capacity. Therefore, on the developed canopy the surface runoff does not form. Plant litter and plant stalks increases the surface roughness of the soil and the resulting increase water absorbing capacity and reduce erosion. In addition, vegetation covers the soil surface and serves as physical protection from the damaging effects of raindrops.

5.4.Soil loss models

For the estimating the soil loss, e.g. for the developing the mathematical ways of description of the detachment, transportation and deposition processes in the eroded soil many empirical, conceptual or physically based models have been derived. Because the soil erosion process is complicated and complex and depend on many conditions, and also considering the field data is often insufficient, evaluation and calibration of soil loss models is a difficult task. The first models for estimation of the effectiveness of agriculture practices and sediments in general were empirical. Empirical models are still used nowadays due to their simplicity and applicability. The general form for the empirical model of soil loss processes can be written as Equation 23 (Holý 1978):

$$S_p = f(X_K, X_H, X_M, X_P, X_G, X_V, X_T, X_{EK}), \tag{23}$$

Where S_p – intensity of soil loss process; X_K – climatic factor; X_H – hydrological factor; X_M – morphological factor; X_P – soil factor; X_G – geological factor; X_V – vegetation factor; X_T – economic and technical factor; X_{EK} – socioeconomic factor (Dvořák and Novák 1994).

RUSLE model

The RUSLE model is a next generation of USLE, it is a Revised Universal Soil Loss Equation. In comparison with USLE, which is a purely empirical model, RUSLE consists of several process-based components. Of course, as the basis of RUSLE include mainly an USLE equation, the structure of model is pretty similar. However, there is a significant improvement in computation of individual factors to increase the general precision The rainfall and runoff factor includes improvements for ponded water and frozen soils. For the soil erodibility factor the seasonal changes are taken into account. The length and slope components consider the rill erosion. There are also improvements in crop and support practices factors (Renard et all 1994).

CREAMS model

CREAMS is a field scale soil loss model for Chemicals, Runoff, Erosion from Agricultural Management Systems. This model is a daily simulation model which computes not only the runoff and sediment transport, but also nutrients and pesticides discharge from fields. The CREAMS is a physically based model. The size of the experimental area should not be bigger than 100 ha (Dvořák and Novák 1994).

The estimation of runoff can be done by two methods, depending on the rainfall data availability. If only the daily data is available, the SCS Curve Number model is used. If the breakpoint rainfall or even hourly data is available, then runoff is simulated by infiltration-based model. The estimation of runoff by both methods is done in order to evaluate the percolation through the root zone of soil. The second part of the model estimates the soil loss with the elements of the USLE, but also includes sediment transport capacity for overland flow (Knisel 1980).

EPIC model

EPIC (Erosion/Productivity Impact Calculator) was developed to estimate the soil productivity, effectiveness of agricultural practices, and soil erosion in United States. This model is also a daily simulation of processes related to erosion, but because the processes of erosion are occurring slowly, the model can estimate the process of soil loss for hundreds of years. It is a physically based model, the mail components of which are: hydrology, weather simulation, erosion-sedimentation, nutrient cycling, plant growth, tillage, and soil temperature. However, the size of the modelled catchment is generally small – less than 1 ha, because the soils and management practices should be identical throughout whole territory on which the simulation is made (Williams et al. 1983).

WEPP model

The WEPP (Water Erosion Prediction Project) model is a relatively newly developed model as a replacement for USLE and RUSLE (Revised Universal Soil Loss Equation) models for soil loss prediction. The main purpose of the model is to estimate the soil loss and sediment discharge on hill slope profiles and small watersheds, the interrill and rill erosion processes are taken into account (Nearing et al., 1994).

The model is quite sensitive to the catchment size, for the hillslope profile it is tens of meters and up to hundreds of meters for small watersheds.

The WEPP model consists of following components: plant growth, climate, water balance, irrigation, infiltration, surface runoff, tillage, soil erosion and sediments yield.

6. The Comments and Discussion

The geomorphological processes continuously form the land surface as the result of an interaction of hydrosphere, geosphere, atmosphere and even biosphere. Since the process is continuous, there is always a need in a new study on it. Nowadays due to the increasing role of human impact and climatic change, the changes in landforms have fastened dramatically. Many studies have been done on the impact of geomorphological factors on different interrelated process.

In the current work the main focus was made on the soil erosion and factors affecting on this process. Of course, soil erosion as a complex process should be studied precisely with taking into account all possible impact. The climatic conditions were studied as the rainfall characteristics, the human impact was described as different types of land use, geomorphological factors are mainly presented as the diversity of landscape, including plane plots, historical terraces and natural slopes.

Those factors were studied with several different methods, using different software and techniques. The following chapter is an overview of applied methods and of existing techniques that could be used to estimate different aspects of the soil erosion process.

The results of following study were published in different scientific journals. Here are presented the most significant ones

Printed:

- Fedorova D., Bačinová H., Kovář P.(2017): Use of terraces to reduce overland flow and soil erosion, comparison of the HEC-HMS model and the KINFIL model application. Soil & Water Res., 12, 2017 (4), 195–201. DOI: 10.17221/160/2016- SWR

- Kovář P., Bačinová H., Loula J., and Fedorova D. (2016): Use of Terraces to Mitigate the Impacts of Overland Flow and Erosion on a Catchment. Plant Soil Environ. Vol.62, no.4.171-177. DOI: 10.17221/786/2015-PSE

- Kovář P., Fedorova D., and Bačinová H. (2018): Implementation of the Curve Numbers Method and the KINFIL Model on the Smeda Catchment to Mitigate Overland Flow with the use of Terraces. Soil & Water Res., 13, 2018 (2), 98–107, DOI: 10.17221/163/2017-SWR

Published Online first:

- Fedorova D., Kovář P., Gregar J., Jelínková A, Novotná J. (2018): The use of Snyder synthetic hydrograph for simulation of overland flow in small ungauged and gauged catchments. Soil & Water Res., 13, 2018 (1): 00–00, DOI: 10.17221/237/2017-SWR

Onward those publications are commented in the form of comparison of applied methods and used software.

6.1 Applied methods for surface runoff estimation

The soil erosion is a complex process, it is a result of interaction of many factors, such as climatic conditions, human impact, geomorphological factors, etc. One of the main processes activating the soil erosion is surface runoff. In this study several methods for surface runoff estimation were applied: Kinematic Wave method, Matrix Inversion method, Curve Number method, two types of synthetic hydrographs: SCS Dimensionless Unit Hydrograph and Snyder’s Synthetic Unit Hydrograph. This part describes each of them more detailed and also includes analysis of results and comparison. Table 5 presents catchments and applied methods.

Table 5. Applied methods for estimation of surface runoff

Catchment	**Applied method**				
	KINFIL	CN	Snyder's SUH	SCS DUH	Matrix Inversion
Kninice	*			*	
Smeda	*	*			
Trebsin	*		*		
Jilovsky					*

Matrix Inversion Model

To estimate the direct runoff Q_n with the given rainfall excess P_m and unit hydrograph U_{n-m+1} is used the discrete convolution equation in the following form (Equation 24):

$$Q_n = \sum_{m=1}^{n\leq M} P_m U_{n-m+1} \tag{24}$$

If there is a need in derivation of the unit hydrograph given the data on rainfall excess and direct runoff, that opposite process is called deconvolution. This process can be used to estimate the unit hydrograph from sophisticated hydrograph, even with several peaks. Unfortunately, with the raising complicity of direct runoff pattern the possibility of errors or nonlinearity in the data in derived unit hydrograph grows significantly. However, there exists an elegant method to avoid that situation: the least-squares optimization method can be a good tool to minimize the nonlinearity and errors. This method was developed by Snyder in 1955 (published in 1961).

The following method was successfully used in a simulation of runoff in the Jilovsky catchment (Fedorova 2018). Despite that matrix inversion model is a quite classical method of estimating the flow and some hydrologists may say it is out of date, it showed an excellent result in this exact case. Coefficient of efficiency for the study on Jilovsky catchment is CE = 0.989, which is considered to be very high. Sadly, this simple, but elegant method is not so widely used nowadays, however it became a basis to a many other methodics partially or even as a full component.

For example, in the study of Kroll and Stedinger (1998), the generalized least squares method was compared with ordinary least squares method, using the components of matrix algebra.

A very interesting work on the convolution integral application in hydrology was made by Okunishi in 1973. The study focuses on the inverse transform of the Duhamel integral – a method to estimate the unknown value of the any of integrands by the known other and the result. It is related to the impact of the output to the input of some system. As a result of the study, author claims that the Kuchment method gives a much more accurate result than the least squares method. The Fourier transform method gives the best results in the given example. However, as author admits the last method is sensitive to the design of filter, while the Kuchment method can be successfully applied in the automatic data processing, when the procedure of transform has to be fixed.

Synthetic Unit Hydrograph

For the hydrological modelling of ungauged watershed when the rainfall or runoff data cannot be observed are widely used different synthetic hydrographs. The synthetic unit hydrographs are based on the experimental data and theoretical assumptions and can be divided on three following groups: the synthetic unit hydrographs based on models of catchment storage; dimensionless unit hydrographs and based on the watershed characteristics (Chow et al 1988).

In the current study two methods of synthetic unit hydrographs derivation are described: Snyder’s Synthetic Unit Hydrograph and SCS Dimensionless Hydrograph.

The Snyder’s synthetic unit hydrograph was developed by Snyder in 1938 and later was modified by more researchers. It is based on relationships between the characteristics of a *standard unit hydrograph* and characteristics of basin morphology – geographical coefficients. Those coefficients can be estimated using the procedure described by Ramirez (2000). Since all synthetic unit hydrographs methods can be applied to the basins with the lack of rainfall-runoff data, Snyder’s unit hydrograph is quite popular method for the overland flow estimation. In the current work the application of this method on the small ungauged experimental area close to Trebsin is described. The Snyder's synthetic unit hydrograph model is a component of a HEC-HMS software, which makes it easy to apply with the right estimation of geographical factors. This simplicity makes the method very appealing to be used for estimation of overland flow on small ungauged catchments, which is proved by several studies. The most related to the current study is the study on Grabinka river catchment in Poland made by Walega (2011). It shows the successful application of this method. In this work it worth to be mentioned that the Snyder's synthetic unit hydrograph method showed slightly better results than the SCS Dimensionless Unit Hydrograph method.

The SCS (Soil Conservation Service), now Natural Resources Conservation Service (NRCS) Dimensionless Unit Hydrograph method is based on the analysis of large amount of watersheds. The X-axis consists of dimensionless time units and Y-axis consists of dimensionless discharge units. This technique is very useful for computing a synthetic unit hydrograph for a wide diversity of watersheds, which totally explains its popularity among researchers.

To estimate the surface runoff with the SCS DUH it is necessary to determine only two parameters: time to peak and peak discharge. The time to peak can be found with the procedure based on lag time and rainfall duration. For the peak discharge estimation it is necessary to precisely determine the geographical factor for given conditions, it mostly depends on the steepness of slope.

The experimental application of following method was made on the location close to Kninice village, on the plot with historical terraces system. The results of application show that the SCS DUH method can be applied for the small basins with the number of assumptions, since the KINFIL model showed a slightly better results. However, as with Snyder's Synthetic Unit Hydrograph the main advantage was in the simplicity of application, as it is also a part of HEC-HMS software.

Generally these two studies made on Kninice and Trebsin experimental areas are very interrelated, both studies are made using the HEC-HMS software and KINFIL model, both studies use different techniques of synthetic hydrographs. These studies are made on ungauged basins, which lack the rainfall-runoff data. The significant differences are in the landforms – Kninice area, as was mentioned above, is the area of historical hedgerows system, which form a meadows terraces belts. While the Trebsin is fully experimental plot, it is divided on several sub-plots with slightly different soil characterists and different crop cultures. These differences should be taken into account while analysing the results of these two studies. Both synthetic hydrographs methods were compared to kinematic wave method, and the Snyder's hydrogrograph shows better results than SCS DUH. However, as was already mentioned, the SCS DUH was applied in the area with sophisticated structure.

Kinematic Wave method

The kinematic-wave method is using the number of approximations of the dynamic-wave model: some terms are neglected as unimportant, the equation of motion assumes that the friction slope is equal to the bead slope. The basic theoretical work on kinematic waves method was done by Lighthill and Whitham (1955). These two scientists gave the name 'kinematic wave' to the new method and discovered the basic characteristics of waves and shock waves based on theory. The use of kinematic-wave method to channel routing has been presented by several scientists: Henderson (1963), Brakensiek (1967), Weinmann and Laurenson (1979). When the channel-water routing or overland-flow routing is calculated by kinematic wave method, it is often called "kinematic model," or "kinematic flow" (Miller and Cunge, 1975).

As was presented in Table 5, the most used method in the current study is Kinematic Wave method (KINFIL model). It shows good results in small ungauged catchments. The KINFIL model belongs to the category of distributed models which are physically based on the theory of infiltration of torrential rains and the transformation of direct runoff on the slopes of basin and in the channel. It uses the physically-geographical characteristics of catchment and hydraulic properties of soil that could be obtained by field measurements or by analysis of cartography data. The purpose of model is to compute the qualitative and quantitative factors that determine the susceptibility of the basin to surface runoff extremes to suggest effective measures on floods and soil erosion control. The model can be applied also on the ungauged catchments. It was primarily designed to derive peak flow rates in various simulations with different input conditions, for example for the change of land use (deforestation, urbanization, etc) (Kovář et al. 2002, 2012, 2016).

The research on different kinematic wave models was done by Shiiba et al (2008). This study describes the basic equations of kinematic flow and some modified kinematic wave models, routing of the kinematic flows on digital terrain models and the lumping methods of kinematic flow.

The idea of comparing different hydrological modelling methods is not new. Good study on this topic was published by Ponce and Simons (1978). Authors compared the diffusion and kinematic wave models. The results of that study slightly resemble the result of the current research.

The Kinematic Wave method showed excellent results in all three catchmnets it was applied on. The main purpose of comparing different hydrological models can be different. It can be an attempt to replace the complicated way of modelling with the easier one, or simply the search of the most accurate results. If the comparison would be made on the accuracy of models, the Kinematic Wave method was the most accurate in all cases, however it required a big amount of data and it was not applied for the catchmnents of bigger scales. Also it was not the easiest model to apply, which can be a serious disadvantage of this method.

CN method

The most important methods in the hydrological modelling and engineering, such as flood design and water balance calculation models, are the simplest ones that does not require much calculations and long data series. (Abon et al. 2011; van Dijk 2010). The Soil Conservation Service Curve Number (SCS-CN) method was originally created by the SCS (US Department of Agriculture), to predict direct runoff volumes for given rainfall events data (SCS 1956, 1964, 1971, 1985, 1993, 2004). Very soon after development it became one of the most popular methods among the engineers and the researchers, due to the simplicity but effectiveness, it is easy to obtain the features and environmental data is available, and it considers many of the factors affecting runoff, including them in a single CN parameter.

However, the opinions on the method are different: it has been long a subject for the both support and criticism (Ponce and Hawkins 1996). The major flaws of the CN method are the dependency on Curve Number (CN) values, fixing the initial abstraction ratio, and absence of clear guidance on how to estimate the Antecedent Moisture Conditions (AMC). In spite of these disadvantages, the method is widely used and is applied in many hydrologic studies. Originally the SCS CN method was developed for agricultural catchments in the mid-western United States, but later it has been used all around the world, with regionally varying additional criteria.

The CN method is based on two processes: the retention (rainfall not converted into runoff) and runoff properties of the watershed and the rainfall.

The Curve Number is a dimensionless parameter, representing the runoff response to the basin characteristics. It depends on many factors, such as: land use, land treatment, hydrological conditions, soil group, and antecedent soil moisture.

The Curve Number method was used in the study on Smeda catchment to supplement the Kinematic Wave method. CN has been correlated with hydraulic conductivity K_s of soil types and also with storage suction factor S_f. The CN values were derived from geographical maps. The values of Curve Numbers (CN) are influenced by land use that in the case of the Smeda catchment is mostly forested.

6.2 Applied software

KINFIL model

KINFIL model is based on the combination of theory of infiltration (INFIL) with the transformation of direct flow by ‘kinematic wave’ method (KIN). For the calculation of infiltration the model uses physically based Green-Ampt method (INFIL) and also indirectly uses the CN curves concept. It computes the surface runoff influenced by anthropogenic activity, such as deforestation, urbanization and crop change, and simulates the significant runoff processes. The model was used and tested in a series of experimental basins for reconstruction of historical flood cases or to simulate various scenarios situations (Jeníček 2005, Jeníček 2010, Kovář et al. 2011, Kovář and Vaššová 2011, Kovář et al. 2015).

The mentioned above Horton’s approach describes the basics of infiltration process, but the physical understanding of the exponential constant is unclear. Green and Ampt (1911) discovered a method, which is based on fundamental physics and also gives results close to the observations. The basic theory of this method is that water percolates into relatively dry soil as a sharp wetting front.

The current version of KINFIL model is based on the infiltration theory of Green and Ampt with the ponding time calculation according to Mein and Larson (1973) and Morel-Seytoux (Morel-Seytoux and Verdin 1981, Morel-Seytoux 1982):

$$K_S\left(z_f + H_f/z_f\right) = (\theta_s - \theta_i)\, dz_f/dt \tag{25}$$

$$S_f = (\theta_s - \theta_i) \cdot H_f \tag{26}$$

$$t_p = S_f/i \cdot \left(\frac{i}{K_S} - 1\right) \tag{27}$$

Where K_s is hydraulic conductivity ($\mathrm{m \cdot s^{-1}}$); z_f is the vertical extent of the saturated zone (m); θ_s is the water content at natural saturation (-); θ_i is the initial water content (-); H_f is the wetting front suction (m); i is the rainfall intensity ($\mathrm{m \cdot s^{-1}}$); S_f is the storage suction factor (m); t_p is ponding time (s), and t is time (s).

On small experimental catchments the hydraulic conductivity K_s and the storage suction factor S_f can be measured directly, but for larger basins it can be problematic. The solution is in the application of the relations between these input parameters and the values of the CN curves. The index values of CN correspond with the conceptual values of soil parameters K_s and S_f :

$$CN = f\,(K_s\,;\,S_f). \tag{28}$$

The second component of the KINFIL model is simulation of the propagation and transformation of direct flow. The resolved partial differential equation describes a continuous motion approximated by a kinematic wave on the given areas, which could be topographically various slopes of planes. This final equation is converted into the shape of finite differentials and is solved by explicit numerous schemes. To design the model the basin is geometrized by dividing on three components: a cascade of planes, convergent and divergent segments and at last the channel of flow (Kovář and Vaššová 2011).

The solution of infiltration process is based on the Green and Ampt theory with Morel-Seytoux adaptation, based on the calculation of the so-called ponding time t_p. There are two parameters in the equations: the hydraulic conductivity K_s (m/s) and the storage suction factor S_f (m):

$S_f = (\theta_s - \theta_i) \cdot H_f$, where θ_s is the saturated soil moisture content (-), θ_i is the initial soil moisture content (-), H_f is the effective capillary suction, θ_{FC} is the moisture content the full moisture capacity. The soil sorptivity for the full field moisture capacity (m/s^{0,5}) would be presented by Equation 29:

$$S(\theta_{FC}) = \sqrt{2K_s \cdot S_f} \tag{29}$$

From the Green and Ampt equation yields:

$$v_f = K_S \cdot \left[i + \frac{(\theta_S - \theta_i) \cdot H_f}{W}\right] \tag{30}$$

Where W is cumulative infiltration (m) and from the Mein and Larson theory (1973) on the determination of ponding time the infiltration equations were derived (Morel-Seytoux 1976).

The overland flow on an impervious slope by a plane (or converging section) can be expressed as the kinematic wave equation:

$$\frac{\partial y}{\partial t} + \frac{\partial q}{\partial x} = i_e(t) \tag{31}$$

$$q = \alpha \cdot y^m \tag{32}$$

Where q is the rate of outflow per unit width of hillslope (m^2/s), y is the depth of flow, $i_e(t)$ is the lateral inflow or excess rainfall intensity (m/s), α, m are the hydraulic parameters, L is the radius of a converging section (m), t and x are the time and space coordinates (s, m).

The result of combination of equations 30 and 31 (Kibler and Woolhiser 1970, Beven 2006) yeilds:

$$\frac{\partial y}{\partial t} + m\alpha y^{m-1} \frac{\partial y}{\partial x} = i_e(t) \tag{33}$$

The kinematic wave model has a solution for depths for depths of flow according to the explicit numerical scheme (Lax, Wendroff 1960):

$$y_j^{i+1} = y_i - \frac{\Delta t}{2\Delta x} \cdot \left(\alpha y_{j+1}^m - \alpha y_{j-1}^m - 2\Delta x (i_e)_j\right) + \frac{(\Delta t)^2}{4(\Delta x)^2} \cdot \left(\alpha y_{j+1}^{m-1} + \alpha y_j^{m-1}\right) \cdot \left(\alpha y_{j+1}^m - \alpha y_j^m - \Delta x \cdot (i_e)_j\right) - \frac{(\Delta t)^2}{4(\Delta t)^2} \cdot \left(\alpha y_j^{m-1} + \alpha y_{j-1}^{m-1} - \Delta x \cdot (i_e)_j\right) + \frac{\Delta t}{2}\left[(i_e)_j^{i+1} - (i_e)_j\right] \tag{34}$$

In the Equation 34 all variables that does not have superscript $i + 1$ are considered in the time step $i(i + \Delta t = t + \Delta t)$. The subscript j labels the space step $x(j + \Delta x = x + \Delta x)$.

A numerical stability of the scheme is ensured, if the time and space are in the relationship 35:

$$c \frac{\Delta t}{\Delta x} \leq 1 \tag{35}$$

Where

$$c = m \cdot y^{m-1} \tag{36}$$

The model KINFIL solves not only depths y_j^{i+1}, but also the other variables of overland flow transformation, like hydraulic velocities, v_j^i:

$$v_j^i = \alpha_j \cdot (y_j^i)^{m_j - 1} \tag{37}$$

Shear velocities, $(v_*)_j^i$:

$$(v_*)_j^i = \sqrt{g \cdot Y_j \cdot y_j^i} \tag{38}$$

And shear stresses, τ_j^i:

$$\tau_j^i = \rho \cdot g \cdot Y_j \cdot y_j^i \tag{39}$$

Where α_j, m_j are the hydraulic parameters, Y_j is the bed slope (-), g is the acceleration due to gravity (m/s^2) and ρ is the fluid density (kg/m^3).

In spite of the good results, KINFIL model has a significant shortcoming. The script of the model was made in 90s using the FORTRAN 77 programming language, which is out of date already. It is a big problem for modern computers to read scripts on FORTRAN 77 correctly due to the several specific features of this language such as: no dynamic memory allocation (on the heap); common blocks, equivalence statements old and obsolete constructs clunky style; missing blanks old (legacy) code is usually cluttered, etc.

HEC-HMS software

The HEC-HMS (Hydrologic Modeling System) software was created by the Hydrologic Engineering Center within the U.S. Army Corps of Engineers. The main purpose of software is to compute the rainfall-runoff processes of different catchments. This model is the hydrological rainfall-runoff model, which can provide simulation of extreme rainfall-runoff episodes in the natural and anthropogenic influenced catchments. That is all including water management services.

The predeceasing software HEC-1 has long been chosen as a standard for analysis of hydrological processes. According to classification, the model is a combination of deterministic and concept classes: it is a physically-based, semi-distributed, event-based runoff model. Some part of the hydrological processes are represented as mathematical relations; other components could be calculated by distributed models, such as Green and Ampt for the estimation of direct runoff or ModClark. The new version provides almost similar simulation abilities, though it is more progressive in mathematical analysis, due to the significant development and faster processing of personal computers available today. The new version has a graphical user-friendly interface, which makes it much easier to use. In addition, it contains some new characteristics, like grid cell surface hydrology and continuous simulation.

The flow modelling is done by the analysis of four components of runoff: rainfall, loss (infiltration as a basic part of losses), the hydrograph (unit hydrograph or kinematic wave), and the baseflow. On the basis of measured or predicted hydro-meteorological data the information on the administration in the field of water management systems could be gained; with the schematization of the basin it allows to simulate outflow and estimate the culmination runoff and the beginning and the process of the flood wave.

The any state of constant change of mass or energy in the hydrological system can be described with a mathematical model and in most cases even several types of model are ready for use for computing each flux. The mathematical models can be used under different conditions and for different situations.

The possibilities of this software could be logically divided on three groups. First one consists the adjustment of schematization based on the precipitation data history and the calibration of model. Second one is the conversion of schematization. The last group covers the process of estimation and the statistic of results.

All land area and water resources in a river basin in HEC-HMS is classified either as directly connected impermeable surface or permeable surface. From directly connected impermeable surface all water flows with no occlusion, evaporation, transpiration and infiltration. Part of rainfall on the permeable surface goes to losses (USACE, 2001). There are seven methods for computing losses in the HEC-HMS: SCS Curve Number, Green and Ampt, Deficit and Constant, Exponential, Initial and Constant, Smith Parlange, Soil Moisture Accounting methods.

In the direct runoff element, excess rainfall is converted into direct runoff. The HEC-HMS model allows modeling direct runoff with six different methods: Clark Unit Hydrograph, Kinematic Wave, ModClark, SCS Unit Hydrograph and user-specified S-Graph and Unit Hydrograph methods. USACE (2000) gives some general recommendations for choosing an appropriate direct runoff method: availability of information for parameter estimation and calibration, suitability of the model assumptions, and user preference and experience.

River routing is a process of calculating the travel time and depletion of water flow in open channels. There are six methods included in the HEC-HMS model to calculate river routing: lag, kinematic wave, modified Puls, Muskingum, Muskingum-Cunge standard section, and Muskingum-Cunge 8-point section. USACE (2000) provides a guides on the possible issues to be considered when selecting a river routing technique: backwater effects, floodplain storage, channel slope and hydrograph characteristics, flow network configuration, subcritical and supercritical flow occurrence, and data availability.

Baseflow is a flow of water from groundwater aquifers that returns to the stream or land surface. The baseflow reduces logarithmically with the values of hydrograph recession curve or is computed on the basis of soil moisture. For the modelling of short rainfall-runoff events, such as flash-floods, the baseflow is usually insignificant component for the simulation of flood hydrographs, however, it is quite important for modelling recession limb or to estimate the volume of flood more accurately. The HEC-HMS model includes three methods for modeling baseflow: constant monthly, linear reservoir, and recession. The constant monthly method is simple technique that uses a constant baseflow at all time steps falling within a particular month. The linear reservoir method can only be used together with the Soil Moisture Accounting loss method. The recession method uses an exponentially decreasing base flow developed from standard baseflow separation techniques.

The HEC-HMS software is user-friendly with intuitively understandable interface. The software is being updated to provide better choice of methods for flow simulation. It is very applicable, it can be used together with other products of U.S. Army Corps of Engineers and GIS technologies. Also the big advantage of this software is availability – it is free and no licence is needed.

7. Publications

Use of terraces to mitigate the impacts of overland flow and erosion on a catchment

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ABSTRACT

The paper presents the impact of a historical system of terraces constructed centuries ago to mitigate the effect of a steep slope on overland flow. Systems of this type were constructed in past centuries by land owners, who then ploughed the land and grew crops on it. They used stones collected from the local agricultural fields as their terracing material. The influence of terraces on overland flow was simulated using the KINFIL. The overland flow is therefore reduced by greater infiltration of extreme rainfall excess flows on the terraces, and the KINFIL model shows to what extent the system of terraces can mitigate the resultant flood and soil erosion. The Knínice locality in North-Western Bohemia, with seven terraces and six field belts between them, was selected as the experimental catchment area. The results compare hydrographs with N-year recurrence of rainfall-runoff time, where N = 10, 20, 50, and 100 years, and the hydraulic variables, e.g. overland flow discharges of a design rainfall, hydraulic depths, flowing water velocity, and shear stress. The comparison provides hydraulic results with terraces and without terraces. The contrast between the results with and without terraces shows the positive role of the system of terraces in protecting the field belts.

Keywords: extreme precipitation; infiltration intensity; soil protection

INTRODUCTION

In many mountainous parts of the landscape in the Czech Republic, there are localities with a dominant slope length parameter that can be interrupted by steps, by terraces, or by hedgerows. These technical and biotechnical measures were made by landowners since the late Middle Ages, when these highland areas were first colonized (Lőw and Míchal 2003). Extensive agriculture has had a long tradition in North-Western parts of Bohemia. Steep slopes were protected by terraces made from stones collected from neighbouring fields. This practice kept many people alive, from the beginning of colonization up to the middle of the 20th century. The dimensions of the terraces vary according to the geographical diversity of the landscape, according to the height, width and length values in relation to the slope angles and slope lengths. All historical remnants of mediaeval landscape have important landscape formation and landscape stabilization attributes (Mérot 1999, Marshall and Moonen 2002). The best positioning of the prevailing axis of the terraces corresponds with the direction of the contour lines when the direction of the water flow is perpendicular to them. This can mitigate overland flow and protects the effective field belt. These belts transform part of the flow, reduce its velocity, and enable it to infiltrate due to greater hydraulic conductivity.

MATERIAL AND METHODS

Description of the simulation is provided in Figure 1 and Figure 2. Figure 1 shows a map of a standard geographical situation with marginal views (on the left), where the terraces are covered by trees and shrubs which, from above, look like hedgerows. Figure 2 provides the scheme of the placement of typical stone terraces that serve as measures in support of infiltration and for mitigating overland flow discharges. A detailed view of two neighbouring terraces is provided in Figure 3. Their construction provides effective obstacles to overland flow, offering high water permeability through a stone body with various diameters, thus reducing the hydraulic velocity. There is usually also a high diversity of vegetation.

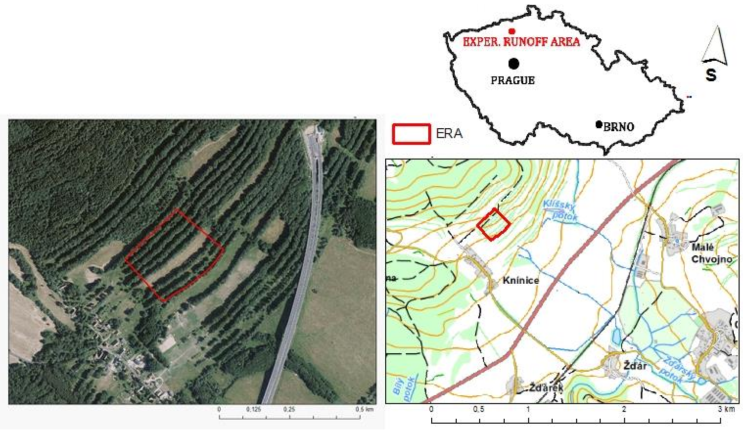


Figure 1. Situation of the Knínice village

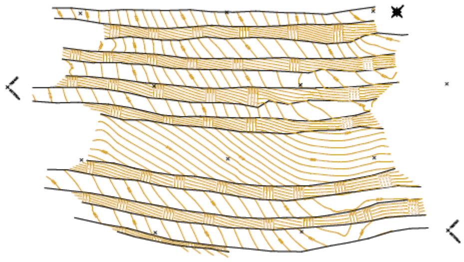


Figure 2. Situation of the experimental runoff area – 1:3000

A number of these terraces are characteristic for the area of the Ore Mountains (Krušné hory), Adolfov, Fojtovice, Libouchec and the northern part of the Central Bohemian Uplands (Orlík and Verneřice). The Libouchec experimental runoff area in the Knínice region in the Ore Mountains is well protected, and its terraces still provide good soil erosion control. This area was therefore selected as a case study area to test the differences in discharges between a steep slope that was not protected in the past and a slope protected by terraces. Using the infiltrometer measurements, it was found that the terraces at Knínice are more than 0.5–0.6 m in depth, and their upper edges are usually higher (by 0.10–0.30 m) than the neighbouring land.

Experimental area. The Knínice experimental runoff area (ERA) is one of the best-protected areas in the Ore Mountains as regards soil erosion. The reference system of terraces is effective and reliable. It is 8.80 ha in area, with 7 terraces and 6 field belts between them. The only drawback with this catchment is that it is ungauged. The geodetic measurements were carried out by the

GMSS Trimble-type total station. The processing was executed using the Geodimeter 640 by the polar method, and the mapping was carried out within the Kokes system, version 1250 (Gepro, Prague, Czech Republic). The final mapping was amended in the Atlas system (Atlas, Prague, Czech Republic).

The average elevation of the catchment is 517.0 m, and the catchment ends not with a single outlet profile, but with an open contour line profile which is about 400 m in width, transferring the surface runoff down to the rest of the catchment, where the slope is gentler. Slope J downstream within the catchment on arable land (nowadays permanent grassland) is J_{PG} = 0.04 to 0.12, and on the terraces the slope is J_{TER} = 0.34 to 0.61.

Figure 3 shows the principle of the longitudinal profile of a typical pair of terraces with one field belt between them. The complete longitudinal profile of the whole system of protective terraces is shown in Table 1. The width was rounded to 400.0 m, and the Manning roughness coefficient n was assessed to be 0.100 on the fields and 0.150 on the terraces (Fread 1989).

The climate in the catchment area is mild-warm and humid. The average annual temperature is between 6.5°C and 7.0°C, and the long-term annual precipitation varies between 650 to 750 mm. The geological structure of the study area is mainly of leistocene orthogenesis and quaternary stony and stony-loam sediments. The dominant soil type consists of mesotrophic to entropic Cambisols, which can be characterized as water-permeable silt loam and sandy loam.

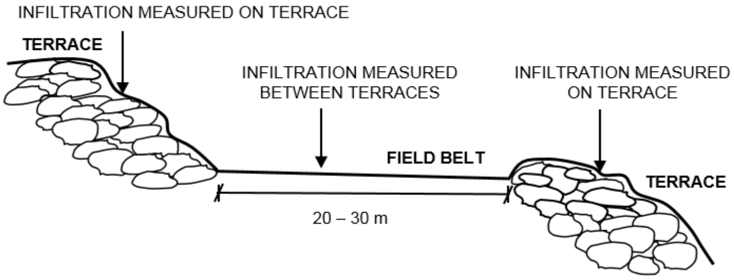


Figure 3. Scheme of terraces protecting field belts against soil erosion. Infiltration parameters are measured on both terraces and on field belts

Table 1. Experimental runoff areas and the fragmentation of the Knínice catchment

Fields	Length (m)	6.00	20.60	17.90	13.70	48.50	21.50	19.40	∑ **147.60**
	Slope (-)	0.04	0.07	0.06	0.04	0.12	0.05	0.04	
Terraces	Length (m)	11.30	10.70	13.90	10.40	12.40	10.70	3.70	∑ **73.10**
	Slope (-)	0.36	0.43	0.37	0.45	0.35	0.34	0.61	

Table 2. Measurement of soil hydraulic values: Hydraulic conductivity K_s (mm/h), Sorptivity S ($mm/h^{0.5}$), and Storage suction factor S_f (mm) and average values on terraces and on fields

Number of measurements		**1.**	**2.**	**3.**	**4.**	**average**
Hydraulic conductivity		29.0	32.0	26.0	33.0	30.0
Sorptivity	on terraces	34.2	33.5	32.6	38.0	34.6
Storage suction factor		20.2	17.5	20.4	21.9	20.0
Hydraulic conductivity		5.0	9.0	6.0	8.0	7.0
Sorptivity	on fields	17.0	22.4	19.4	20.3	19.8
Storage suction factor		28.9	27.9	31.4	25.8	28.0

Field measurements. The procedure of the Richards equation (Kutílek and Nielsen 1994) and the Philip's solution for non-steady flow infiltration (Philip 1957) was used. The shortened Philip equation for the infiltration intensity v_f into the soil with saturated hydraulic conductivity K_s (mm/h) and sorptivity ($mm/h^{0.5}$), has the form:

$$v_f\ (t) = \frac{1}{2}\, S\, .\, t^{-1/2} +\ K_s \qquad (1)$$

Subsequently, parameters K_s and S were both computed, applying the method of the non-linear regression (Kovář et al. 2011, Štibinger 2011). Table 2 provides the values of the measurements of hydraulic conductivity K_s and also sorptivity S, measured four times each in four terraces and four fields. This table also shows the average values of K_s and S, and also provides the storage suction factor S_f (mm):

$$S_f = \frac{S^2}{2K_s} \qquad (2)$$

The final parameter values are given in Table 2. The average storage suction factor for fields is S_f = 28.0 mm, and for terraces is S_f = 20.0.mm. The K_s value for the terraces is about 4.3 times higher than for the field belts. The *S* value for the terraces is about 1.7 times higher than *S* value for the field belts.

Extreme rainfall assessment. The Knínice catchment uses the rainfall data from the Ústí nad Labem – Kočkov station, which is located 9 km away. This rain gauge provides daily rainfall data with a return period N = 2, 5, 10, 50 and 100 years, as shown in Table 3. Due to the small catchment area, the periods of critical rainfall duration were selected for time t_d = 10, 20, 30 and 60 min and a return period of N = 10, 20, 50 and 100 years. The DES_RAIN procedure (http://fzp.czu.cz/vyzkum) was used to compute the reduction in the daily rainfall depths $P_{t,N}$, (Kovar et al. 2011). This procedure is based on regional parameters a and c, which were derived using the methodology by Hrádek and Kovář (1994) with the results provided by Table 3, where $P_{t,N}$ is the maximum extreme rainfall depth (mm), less than 1 day duration and return period N years.

Table 3. Maximum extreme rainfall depths $P_{t.N}$ of short duration in the station Ústí nad Labem (mm)

N	***$P_{t.N}$***	***t* (min)**			
(years)	**(min)**	**10´**	**20´**	**30´**	**60´**
2	30.6	10.1	12.4	14.0	16.3
5	41.8	14.7	18.2	20.7	24.8
10	49.0	17.6	22.4	15.7	30.7
20	56.5	21.5	27.4	31.6	38.0
50	65.7	26.3	33.8	39.2	47.5
100	79.2	32.5	42.1	49.1	59.4

The value of one-day extreme rainfalls $P_{1d,N}$ was used from the published rainfall data records of the series from 1901 to 1980 (Šamaj et al. 1983). These short-duration extreme rainfalls were tested using the KINFIL rainfall-runoff model.

KINFIL rainfall-runoff model. The 3D KINFIL model accepts two parts of the hydrological process. The first part is infiltration of rainfall to create rainfall excess, and the second part is the overland flow production from rainfall excess and its transformation into a final runoff hydrograph. The model also has marginal results, e.g. hydraulic depths and velocities. It is physically based, and was been used since 2002 for simulating rainfallrunoff processes on gauged and ungauged catchments (Kovář et al. 2002). Since 2002, the model has been supplemented to simulate the hydraulic processes needed for shear stress values to compute erosion (Kovář et al. 2011).

The rainfall excess r_e (t) is computed by subtraction from the extreme rainfall intensities i (t) of return period *N* in order to obtain the rainfall excess hyetograph r_e (t):

$$r_e(t) = i\,(t) - v_f\,(t) \tag{3}$$

This infiltration part of the KINFIL model is based on the infiltration theory of Green and Ampt, applying the concept of ponding time and the storage suction factor S_f by Morel-Seytoux and Verdin (1981) and by Morel-Seytoux (1982):

$$v_f = (\theta_s - \theta_t)\frac{d_{zf}}{dt} = K_s\left[\frac{z_f + H_f}{z}\right] \tag{4}$$

The left-hand side of eq. (4) expresses the Darcy principle for the infiltration process v_f(t), while the right-hand side of the equation reflects the Green-Ampt theory (Rawls and Brakensiek 1983). The Darcy principle has been used by many authors (e.g. Morel-Seytoux and Verdin 1981). In eq. (4), $(\theta_s - \theta_t)$the difference between the saturated soil moisture content and actual content (-), z_f is the depth of the infiltration front, and z is the vertical ordinate (both in m). K_s is the hydraulic conductivity (m/s), and H_f is the capillary suction on the infiltration front (m).

The second part of the KINFIL model is the overland flow component, using the kinematic equation (Kibler and Woolhiser 1970, Beven, 2006):

$$\frac{\partial y}{\partial t} + \alpha\,.\,m\,.\,y^{m-1}\,.\frac{\partial y}{\partial x} = r_e(t) \tag{5}$$

where r_e (t) is rainfall excess intensity (m/s), y, t, x are ordinates of the depth of water, time and position (m, s, m), and α, m are hydraulic parameters. This equation describes non-steady flow, approximated by a kinematic wave on a plane or a cascade of planes or segments. It is computed using the finite differences scheme [Lax and Wendroff, 1960]. The upper boundary condition of the Lax-Wendroff scheme is $y\,(x, 0) = 0$ for all values of x. Fig. 4 shows the view of the longitudinal profile, and Table 2 provides the measured parameters. This system puts emphasis on the geometry of the planes, their slopes and the hydraulic roughness conditions.

RESULTS AND DISCUSSION

The simulation by the KINFIL model was implemented for all events in the return periods of their duration t_d = 10′, 20′, 30′, and 60′ for the basic scenario without terraces and with terraces, to see how much they reduce the overland flow discharges. The sub-catchment areas were fragmented to reflect the fact that each field belt has one biotechnical protective measure in the form of a terrace. The geometric dimensions of the terraces correspond to the real situation. The final results are shown in Table 4 and Fig. 4.

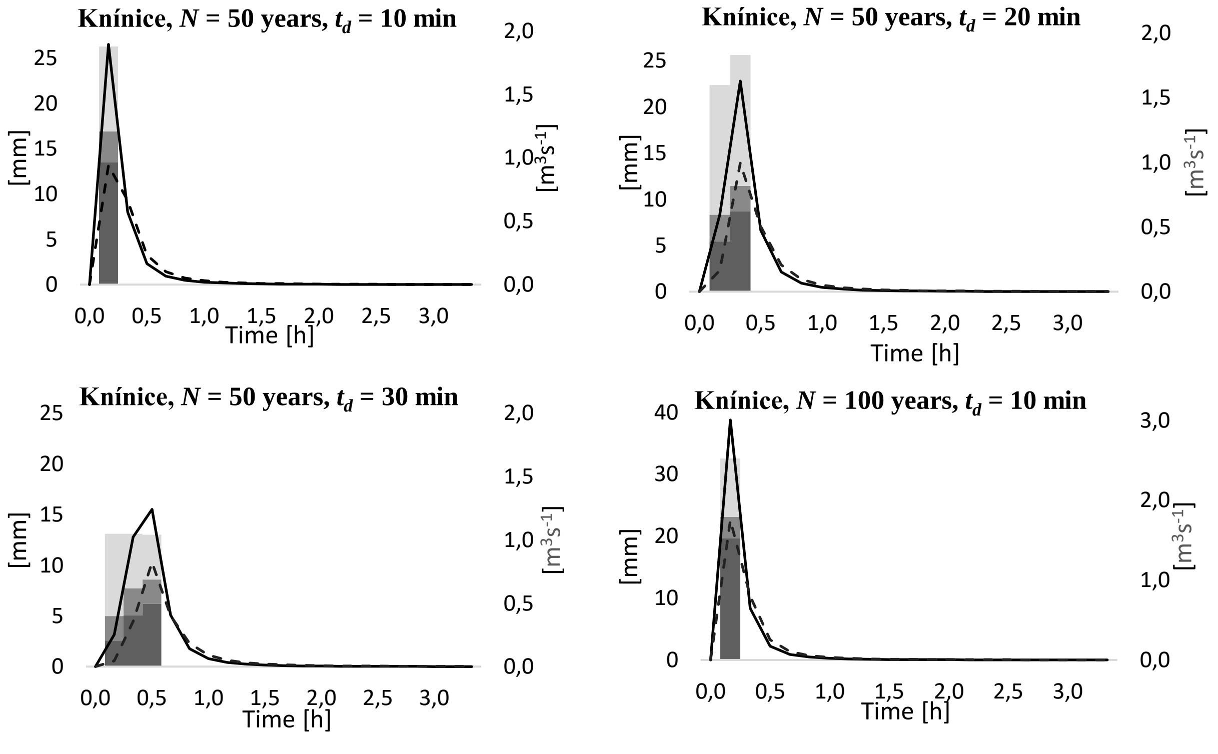
The highest values of the hydraulic variables are on N = 100 years rainfall with 10 min duration when the depth of overland flow is about 0.2 m, hydraulic velocity 0.34 m/s and the shear stress is about 42.0 Pa.

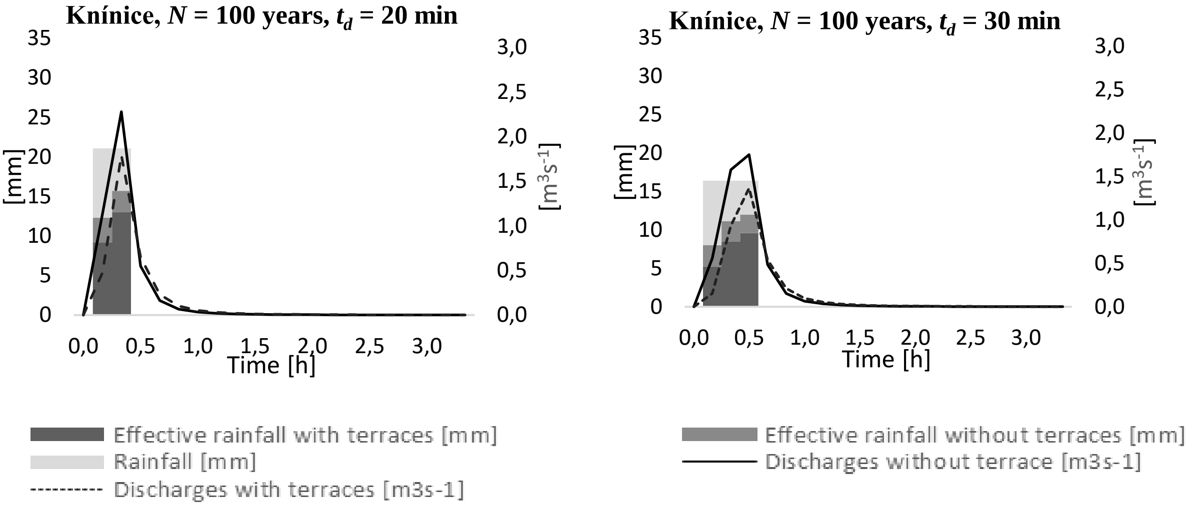
There are a few hydrological models that can simulate infiltration and overland flow processes on agricultural bench terraces (e.g. Amore et al. 2004, Zhas et al. 2000, Askoy and Kavvas 2005). A simpler geomorphological system of erosion control usually provides better modelling (Maidment 1992). The terrace system at Knínice is a good example. An analysis of the effects of terrace configuration on peak flow, and on the delay to peak flow on an undisturbed hillslope can also provide information leading to improved land management (e.g. Hallema and Moussa 2014, Vetter et al. 2014).

Table 4. Major rainfall parameters and runoff hydrograph peaks on the Knínice catchment without terraces and with terraces

N (years)	Duration time t_d (min)	Rainfall depth (mm)	Effective excess (mm)		Hydrograph peak (m^3/s)	
			Without terraces	With terraces	Without terraces	With terraces
10	10	17.6	8.38	5.31	0.60	0.19
10	20	22.4	8.71	4.08	0.61	0.13
10	30	25.7	8.39	2.78	0.52	0.08
10	60	30.7	5.21	0.18	0.23	0.06
20	10	21.5	12.18	8.89	1.11	0.45
20	20	27.4	13.49	8.23	1.09	0.41
20	30	31.6	13.90	7.07	0.85	0.31
20	60	38.0	11.19	2.32	0.43	0.09
50	10	26.3	16.94	13.52	1.89	0.94
50	20	33.8	19.78	14.17	1.63	0.99
50	30	39.2	21.30	13.77	1.24	0.82
50	60	47.5	20.00	8.28	0.69	0.33
100	10	32.5	23.12	19.65	3.00	1.75
100	20	42.1	28.03	22.27	2.28	1.79
100	30	49.1	31.12	23.26	1.75	1.37
100	60	59.4	31.62	18.41	0.99	0.66

Figure 4. Hydrographs comparison on the Knínice catchment with a terrace infiltration function and without it, for extreme rainfalls of various return periods *N* and time periods t_d





CONCLUSION

In conclusion, slope terraces have distinct hydrophysical characteristics that are different from the characteristics of field belts where there is permanent grassland growing between them. The area of the field belts in the Knínice study area is about 2/3 of the 8.80 ha sub-catchment and the rest of the area is taken up by terraces. One third of the farmer’s arable land has to be taken out of agricultural productions. As a result of their favourable infiltration characteristics, the terraces act as biotechnical infiltration and erosion control measures for decreasing the overland flow. They may also have an important influence on the water regime during dry seasons.

Simulations using the KINFIL model have proved that, due to the favourable infiltration characteristics of the soils in the Knínice catchment, the hydraulic depth of the overland flow for gross rainfall with return periods of $N = 2$ and 5 years is insignificant (see Table 4). The discharges caused by rainfall with a return period of $N = 10$, 20, 50, and 100 years could be harmful if there were no terraces. In the most critical runoff Q_{100} (10´), the discharges are reduced by the terrace system from a value of 3.00 m^3/s to a value of 1.75 m^3/s (i.e. by 42%).

However, if the plots of permanent grassland were to be transformed into arable land for growing field crops, there would surely be inadequate protection, due to the changes in the critical shear stress of soil that is not covered by permanent grassland.

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Use of Terraces to Reduce Overland Flow and Soil Erosion, Comparison of the HEC-HMS Model and the KINFIL Model Application

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ABSTRACT

In our study, a system of seven natural terraces interspersed with six field belts situated at the Knínice locality (the Ore Mts., North-West Bohemia) was selected as the experimental catchment area. Overland flow was computed using two different methods: the kinematic wave method and the SCS dimensionless Unit hydrograph (UH). For the kinematic wave method calculations the KINFIL software was used; for SCS dimensionless hydrograph the HEC-HMS software was applied. The results compare hydrographs with N-year recurrence of rainfall-runoff time, where N = 10, 20, 50, and 100 years. The comparison provides hydraulic results with terraces and without terraces computed using both mentioned software products. Although two different methods of overland flow computation were performed, the input data obtained from geodetic and hydrological measurements were identical. Results of the comparison are presented and discussed.

Keywords: extreme rainfall; infiltration; kinematic wave; soil protection; Unit hydrograph

In many mountainous parts of the Czech Republic there are locations with agricultural hedgerows, agricultural terraces, walls, because these measurements allow fields to be founded even on steep slopes. Usually terrace consists of flat part, which could be used as field and the slope part. However, considerable part of the hedgerows was, in the long term, excluded from cultivation. Typical terraces have a high diversity of vegetation. The described location is characterised by grass areas in combination with stony hedgerows between them. The borderlines are underlined by trees and shrubs. Terraces serve as an effective barrier for surface runoff, thanks to the stone design with different diameters showing high water permeability, thereby reducing the hydraulic speed. Currently, there are ongoing discussions about the character and applicability of the model of kinematic waves. This paper deals mainly with the question whether the kinematic wave model can alternatively replace other proven methods of runoff generation, such as a dimensionless Unit hydrograph, for calculating the overland flow in mountainous regions with a historical system of terraces.

MATERIAL AND METHODS

Experimental area. The experimental catchment area at Knínice constituted by seven terraces interspersed with six field belts is much larger (8.80 ha) than the Libouchec Experimental Runoff Area (ERA) sizing 2.21 ha. The experimental area is described in Figure 1 showing a map of standard geographical situation with marginal views (on the left), where the terraces are covered by trees and shrubs which, from above, look like hedgerows.

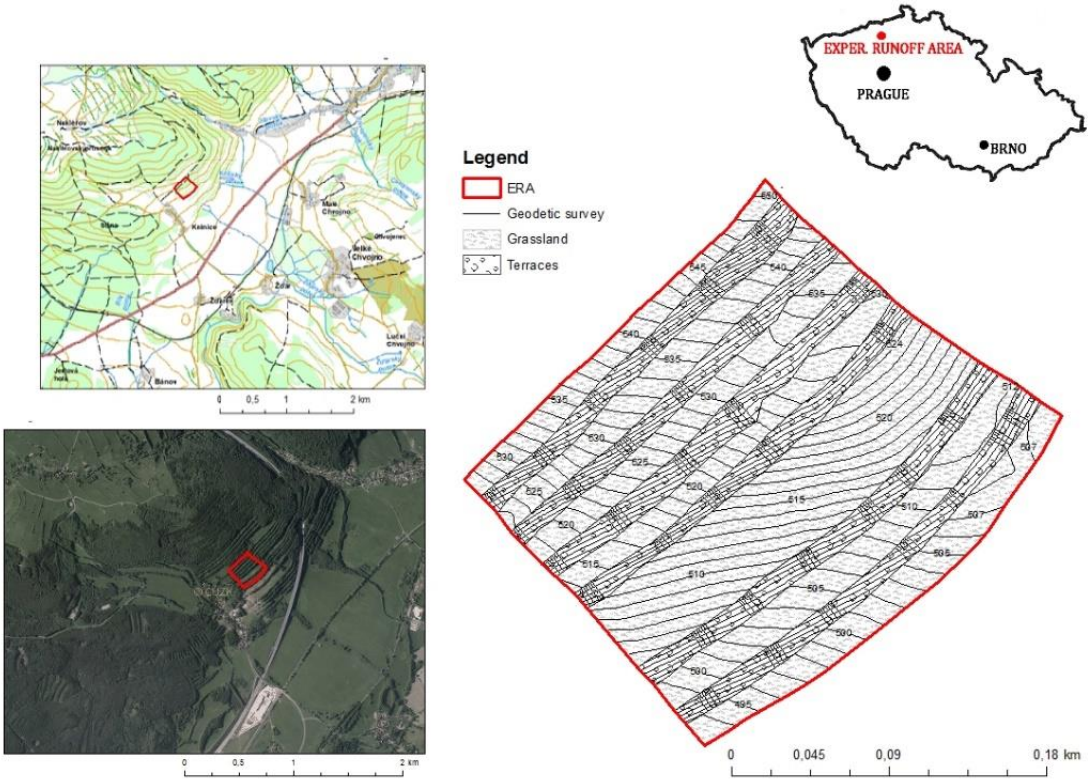


Figure 1. Location of the Knínice village and the Experimental Runoff Area (ERA) and a scheme of terraces protecting field belts against soil erosion

On the right side there is the village of Knínice on the map of the Czech geodetic survey. Figure 2 provides the schematic placement of typical stone terraces that serve as measures in support of infiltration and for mitigating overland flow discharges, and gives a detailed view of two neighbouring terraces. Terraces serve as an effective barrier for the surface runoff, which thanks to the stone design and different diameters are highly water permeable, thereby reducing the hydraulic velocity. Typical terraces have a high diversity of two-level vegetation (shrubs and trees).

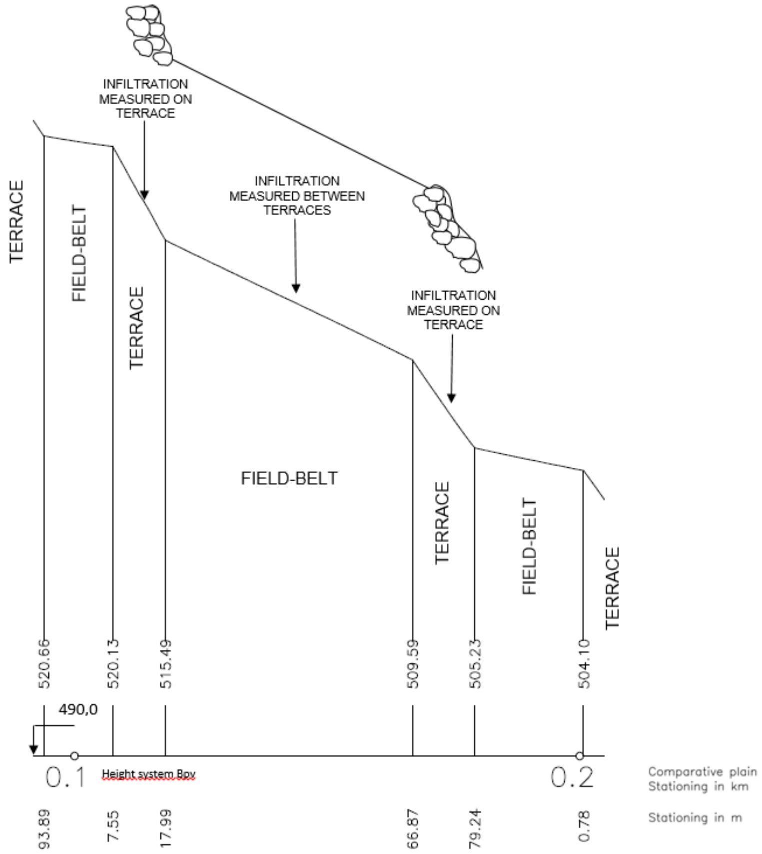


Figure 2. Section of the scheme of terraces protecting field belts against soil erosion; longitudinal profile of the terraces and the field belt system (1 : 1000/250); infiltration parameters are measured on both terraces and on field belts

The Libouchec ERA in the Knínice region in the Ore Mts. is well protected, and its terraces still provide good soil erosion control in this area. The average elevation of the catchment is 517.0 m a.s.l. The catchment ends with an open contour line profile which is about 400 m wide. Slope variation downstream within the catchment on arable land (this part of land is permanently overgrown with grass) is $J_{PG} = 0.04$ to 0.12, and on the terraces the slope variation is $J_{TER} = 0.35$ to 0.61. The complete longitudinal profile of the whole system of field belts alternating with protective terraces is depicted in Table 1.

Table 1. Parameters of individual terraces (1–7) and field belts constituting the Knínice catchment area

		1	2	3	4	5	6	7
Terraces	length (m)	11.30	10.70	13.90	10.40	12.40	10.70	3.70
	slope (-)	0.36	0.43	0.37	0.45	0.35	0.34	0.61
Fields	length	6.00	20.60	17.90	13.70	48.50	21.50	19.40
	slope	0.04	0.07	0.06	0.04	0.12	0.05	0.04

Climate is mild-warm and humid. Long-term annual precipitation average is 650–750 mm. The average annual temperature is 6.5–7.0°C. Geological structure of the ERA is mainly of pleistocene orthogenesis and quaternary stony and stony-loam sediments prevail. The dominant soil types are mesotrophic to entropic Cambisols, which can be characterized as water-permeable silt loam and sandy loam. Field measurements. For the measurement of geodetic data we used a Trimble total station with GNSS options. Data were processed by a Geodimeter System 640 using the polar method. Mapping was carried out within the KOKES system, version 1250. The final mapping was amended in the ATLAS system. For the infiltration measurement, the procedure of the Richards equation (Kutílek & Nielsen 1994) and the Philip solution for non-steady flow infiltration (Philip 1957) are crucial. The shortened Philip equation for the infiltration intensity (v_f) into the soil, calculated with the saturated hydraulic conductivity K_s (m/s) and sorptivity S (m/s$^{1/2}$), is as follows (Eq. 1):

$$v_f\ (t) = \frac{1}{2}\, S\, .\, t^{-1/2} + K_s \tag{1}$$

Both parameters K_s and S were computed using the method of non-linear regression (Kovář et al. 2011; Štibinger 2011). Table 2 provides the results of hydraulic conductivity K_s and sorptivity S measurements, each carried out four times in four terraces and four fields. Table 2 shows also the average values of K_s and S, and the storage suction factor S_f (mm) calculated according to Eq. (2):

$$S_f = \frac{S^2}{2K_s} \qquad (2)$$

The final values of calculated parameters are given in Table 2. The average storage suction factor S_f is 28.0 mm for the fields and 20.0.mm for the terraces. The K_s value for the terraces is about 4.3 times higher than for the field belts. The S value for the terraces is about 1.7 times higher than for the field belts.

Table 2. Hydraulic values measurements on fields and terraces

		Average	Number of measurements			
			1	2	3	4
S ($mm/h^{0.5}$)		19.8	17.0	22.4	19.4	20.3
K_s (mm/h)	on fields	7.0	5.0	9.0	6.0	8.0
S_f (mm)		28.0	28.9	27.9	31.4	25.8
S ($mm/h^{0.5}$)		34.6	34.2	33.5	32.6	38.0
K_s (mm/h)	on terraces	30.0	29.0	32.0	26.0	33.0
S_f (mm)		20.0	20.2	17.5	20.4	21.9

Extreme rainfall assessment. The Knínice catchment uses the rainfall data from the Ústí nad Labem – Kočkov station situated 9 km apart. This rain gauge provides daily rainfall data with a return period N = 2, 5, 10, 50, and 100 years (Table 3).

Table 3. The maximum of the extreme rainfall depths $P_{t.N}$ of short duration in the station Ústí n. L. (in mm)

N	***$P_{t.N}$***	***t* (min)**			
(years)	**(min)**	**10´**	**20´**	**30´**	**60´**
2	30.6	10.1	12.4	14.0	16.3
5	41.8	14.7	18.2	20.7	24.8
10	49.0	17.6	22.4	15.7	30.7
20	56.5	21.5	27.4	31.6	38.0
50	65.7	26.3	33.8	39.2	47.5
100	79.2	32.5	42.1	49.1	59.4

Because the Knínice catchment represents a small catchment area, the periods of critical rainfall duration were selected just for time t_d = 10, 20, 30, and 60 min and a return period of N = 10, 20, 50, and 100 years. The DES_RAIN software was used for computing the reduction in daily rainfall depths $P_{t,N}$ (Kovář & Vaššová 2011). This procedure is based on regional parameters *a* and *c*, derived following the methodology of Hrádek and Kovář 1994. The results of data simulation are presented in Table 3. $P_{t,N}$ is the maximum extreme rainfall depth (mm) less than 1 day duration and return period N years.

The HEC-HMS (Hydrologic Modeling System) software is a new generation product of the Hydrologic Engineering Center within the U.S. Army Corps of Engineers (USACE 2013). It is designed to simulate the precipitation-runoff mechanisms of dendritic drainage basins and it is a replacement for HEC-1, which has long been considered a standard for hydrologic simulation (Zhang et al. 2013). The new HEC-HMS is capable of almost similar simulation, but it is more advanced in numerical analysis, which is a significant advantage of the modern faster desktop computers. It also has a number of features that were not included in HEC-1, such as continuous simulation and grid cell surface hydrology. The graphical user interface makes the software more user-friendly.

The runoff from any size basins is calculated using four processes of flow from the catchment area, taking into account the division or merger of the channel. The runoff hydrographs are computed using data of rainfall, excess loss (infiltration), Unit hydrographs or kinematic wave, and the baseflow. Any mass or energy flow in the cycle can then be described with a mathematical model. Several model choices are usable for describing each flow in most cases. Each mathematical model included in the software is relevant for different environments and under different conditions.

The loss can be computed using the SCS Curve Number, Green and Ampt, Deficit and Constant, Exponential, Initial and Constant, Smith Parlange, Soil Moisture Accounting methods. The Unit hydrograph can be made based on Clark Unit Hydrograph, Kinematic Wave, ModClark, SCS Unit Hydrograph, and user-specified S-Graph and Unit Hydrograph methods. The baseflow decreases logarithmically with the set value of hydrograph recession curve or is calculated on the basis of soil moisture. Averaged catchment rainfall can be calculated by precipitation at certain points by using standard weighing method or probability criterion of maximum rainfall, or on the basis of gridded radar precipitation data. The methods of hydrograph calculation also include Muskingum, Muskingum-Cunge, Kinematic Wave, and Modified Puls methods. The Modified Puls method is used primarily for reservoirs. The model can be made both on the confined parts of a basin or on the spatially distributed gridded basins. Internal calculations are performed in the metric system, input and output data can be both in metric and U.S. Customary unit systems.

The HEC-HMS software Unit hydrograph method was successfully used for modelling runoff in Romania as was discussed in the study of Györi and Haidu (2011). The HEC-HMS Rainfall-Runoff model was computed for flow simulation on three basic models: the climatic model, the catchment model, and the control indices. The loss method calculates an effective rainfall with the input hyetograph, the results are transformed in a function that converts the excess precipitation into runoff at the subwatersheds outlets. **Soil Conservation Service dimensionless hydrograph.** The dimensionless unit hydrograph has been developed by the Soil Conservation Service (SCS) from the Unit hydrographs for a high number of basins of different sizes and for many different environments. The SCS dimensionless hydrograph is a synthetic Unit hydrograph in which the discharge is described as a ratio of discharge (q) to peak discharge (q_p) and the time by the ratio of time (t) to time of peak of the Unit hydrograph (t_p). The Unit hydrograph can be determined from the synthetic dimensionless hydrograph for the given basin given the peak discharge and the lag time for the duration of the excess rainfall (Ramírez 2000). The dimensionless Unit hydrograph can be expressed in terms of an equivalent triangular hydrograph as suggested by the SCS. Using this simplified triangular Unit hydrograph the values of q_p and t_p can then be estimated. The height of the simplified Unit hydrograph in this case is equal to q_p and time base t_b is equal to $2.67\ t_p$

(SCS 1972). In SCS, time is usually expressed in hours (h), and the discharge in m^3/s/cm (or cfs/in). The SCS recommends recession duration of $1.67t_p$ after the analysis of a high number of Unit hydrographs. It can be shown that:

$$q_p = C \cdot A / t_p \quad (3)$$

because the volume of direct runoff must equal 1 cm, where C = 2.08 (483.4 in the British system) and A is the drainage area in square kilometres (square miles). The basin lag is

$$t_l = 0.6t_c \quad (4)$$

from a study of many large and small rural watersheds, where t_c is the time of concentration of the watershed. The time to peak, t_p, is then equal to $t_r / 2 + t_l$, (SCS 1972).

The data required by the SCS hydrograph method include mostly hydrological data as channel depth, length, and rainfall data. In order to receive the SCS dimensionless Unit hydrograph it is necessary to estimate the lag time for a given basin. The timing parameter considerably affects the values of the Unit hydrograph, but it is somewhat difficult to estimate and rather subjective (Chow 1959). The 3D KINFIL is a physically based model, it covers two parts of the hydrological process. The first part describes the infiltration of rainfall to build rainfall excess, and the second part expresses the overland flow presentation from rainfall excess and its conversion into a final runoff hydrograph. The model also delivers marginal results, e.g. hydraulic depths and velocities. Since 2002 it has been applied for simulating rainfall-runoff processes in gauged and ungauged catchments (Kovář et al. 2002). Later the model has been improved to simulate hydraulic processes needed for shear stress values to compute erosion when soil calibration is at disposal (Kovář et al. 2012). The overland flow part of the KINFIL model uses the kinematic equation and can be described by Eq. (5) (Kibler & Woolhiser 1970; Maidment 1992; Beven 2006):

$$\frac{\partial y}{\partial t} + \alpha \,.\, m \,.\, y^{m-1} \,.\, \frac{\partial y}{\partial x} = r_e(t) \quad (5)$$

where r_e (t) is rainfall excess intensity (m/s), y, t, x are ordinates of the depth of water, time and position (m, s, m), and α, m are hydraulic parameters.

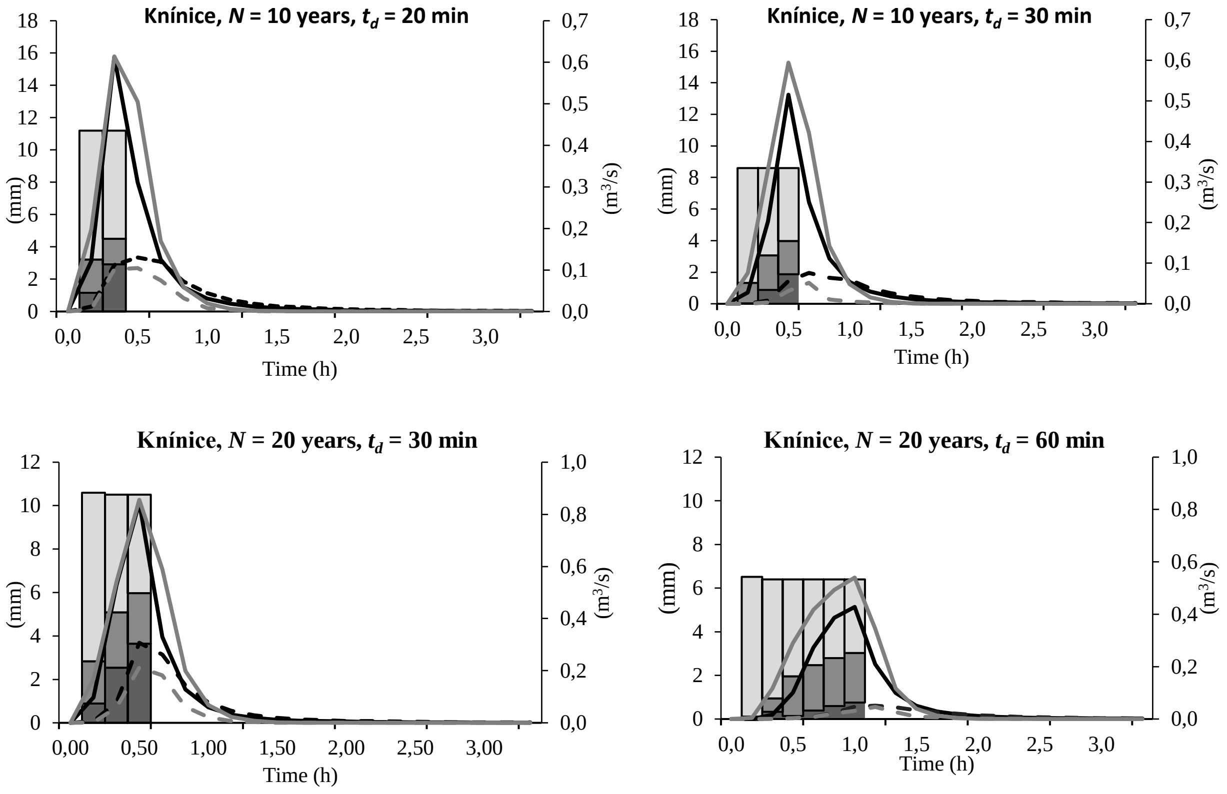
The infiltration part of the KINFIL model is based on the Green and Ampt theory of infiltration, using the principle of ponding time and the storage suction factor S_f (Morel-Seytoux & Verdin 1981; Morel-Seytoux 1982):

$$v_f = (\theta_s - \theta_t)\frac{d_{zf}}{dt} = K_s\left[\frac{z_f + H_f}{z}\right] \tag{6}$$

The right side of Eq. (6) expresses the Green-Ampt theory (Rawls & Brakensiek 1983), the left side describes the Darcy concept for the process of infiltration v_f(t). K_s is the hydraulic conductivity (m/s), and H_f is the capillary suction on the infiltration front (m). In eq. (4), $(\theta_s - \theta_t)$ the difference between the saturated soil moisture content and actual content (-), z_f is the depth of the infiltration front, and z is the vertical ordinate (both in m) (Kovar et al., 2016).

RESULTS AND DISCUSSION

The question if the kinematic wave method can replace the Unit hydrograph methods still remains open due to the huge fundamental differences of these two methods. Researchers and practitioners have reported both on the success and failures of the kinematic wave model (e.g. Hromadka & DeVries 1988; Syed et al. 2012). The kinematic wave method for overland flow is a deterministic and physically based, distributed-parameter, hydraulicdata-intensive method (requiring geometric and frictional parameters), which is primarily applicable to small catchments, for which the perfectionism of the mathematical modelling can be applied in practice, when high detailization can actually reveal the processes occurring in the experimental area. From a number of the kinematic wave models we have selected the KINFIL model. The dimensionless Unit hydrograph performs the typical shape of Unit hydrographs charted in dimensionless terms. The discharge ordinates of this hydrograph are divided by the maximum discharge, and the time ordinates are divided by the time from 10% of peak flow to peak flow to obtain the dimensionless Unit hydrograph. The 10% time is subjective and was used to reduce the long build-up time when the discharge is small (Bender & Roberson 1961). The Unit hydrographs were originally designed for large catchments (Sherman 1932), but later the method was found to be primarily applicable to midsize catchments. Nevertheless, with catchment subdivision, the applicability of the Unit hydrograph can be extended also to large catchments (Wałęga 2013). Due to the fact that the overland flow kinematic wave method is primarily used for small catchments, and the Unit hydrograph is primarily applicable to midsize catchments, it seems these two methods should overlap to a small extent (Ponce et al. 1978). The simulations by the both models were computed for all events in the return periods of their duration t_d = 10, 20, 30, and 60 min for the basic scenario without terraces and with terraces. The sub-catchment areas were fragmented to reflect the fact that each field belt has one biotechnical protective measure in the form of a terrace. The geometric dimensions of the terraces correspond to the real situation. The final results are shown in Figure 3.



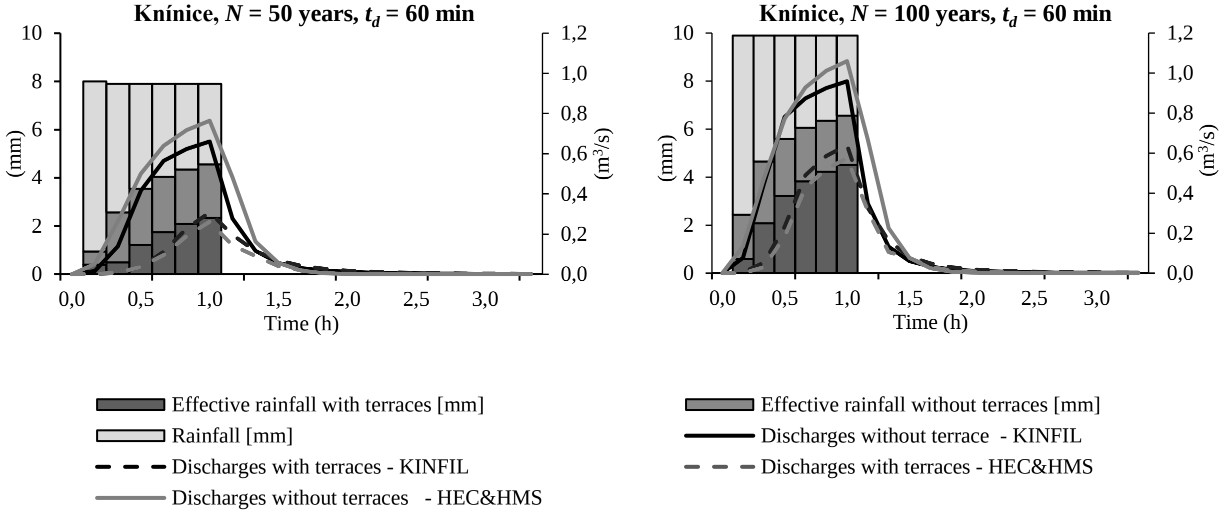


Figure 3. Comparison of hydrographs for the Knínice catchment with and without the terraces for extreme rainfalls of various return periods N and duration periods t_d

CONCLUSION

The dispute which method is better or more accurate has no simple answer. Both methods require different input data, they are of different nature and are not readily comparable. The HEC-HMS software is undoubtedly easier to use even by an unexperienced user, the interface is simplified and can be used intuitively, which is a big advantage of the HEC software. The KINFIL interface is not so user friendly, the kinematic wave method itself requires more data, but it provides more accurate results, as presented in Figure 3. The hydrographs calculated by the kinematic wave method are sharper in shape, which is more natural under given conditions for small catchments. The results yielded by the SCS Unit hydrograph also attain higher values for natural cases, e.g. without terraces, however, the difference in discharges is not very significant, especially for N = 10 and 20 years it is less than 0.1 m^3/s. A significant benefit of the kinematic wave method is that it can describe roughness coefficient and rainfall variations. The model provides also marginal results, e.g. hydraulic depths and velocities. The kinematic wave method increases in accuracy as the catchment size decreases; and the Unit hydrograph methods increase in applicability with the increasing catchment scale.

So, in cases where the scale can be logically negotiated, the kinematic wave model should provide better specification in a future simulation of flood flows.

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Implementation of the Curve Number Method and the KINFIL Model in the Smeda Catchment to Mitigate Overland Flow with the Use of Terraces

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ABSTRACT

The Smeda catchment is a part of the Jizera Mountains located on the north of Bohemia where the Smeda Brook drains the area of about 26 km^2. This experimental mountainous catchment with the Bily Potok downstream gauge profile was selected as a model area for simulating extreme rainfall-runoff proceses using combination of the KINFIL model to be completed by Curve Numbers (CN) method. This method is based on two parts. The first provides the application of CN theory, when CN has been correlated with hydraulic conductivity K_s of soil types and also with storage suction factor S_f at the field capacity FC: $CN=f(K_s, S_f)$. The second part of the combined KINFIL/CN method, represented by the KINFIL model, is based on the kinematic wave method which, in

combination with infiltration, mitigates the overland flow. This simulation was chosen as an alternative to an enormous amount of field measurements. The combination used here was shown to provide a successful method. However, practical application would require at least four sub-catchments, so that more terraces can be placed. The provision of effective measures will require more investment than is currently envisaged.

Keywords: CN method; infiltration; kinematic KINFIL model; wave

Introduction

The discharges in the limnigraphic profile at the outlet of the Bily Potok profile of the Smeda catchment have been measured continuously since 1957. The physical and geometric characteristics of the catchment are provided in Table 1. The catchment area is 26.13 km^2.

Table 1. Physical and geometric characteristics of the Bily Potok profile of the Smeda catchment

Characteristics	**Value**
Catchment Area (AR, km^2)	26.13
Length of talweg (L, m)	13 300
Slope of talweg (J, %)	6.9
Potential retention (A, mm)	74.0
Elevation (m a.s.l.)	403–990
Average width of the catchment (km)	1.96
Slope of the catchment (Herbst) (%)	22.2

MATERIAL AND METHODS

Smeda catchment. Table 2 presents the hydrological situation and the N-year discharges. Table 3 documents the calculation of the average value of the Curve Number CN_{II} = 77.5. This value is relatively high, and indicates low infiltration capacity through the hydrologic soil group C (77%). The remainder of the soils belongs to the hydrologic group B, i.e. soils with low sorptivity (oligomesotrophic soils, podzolic peat-brown soils, and peaty-gley soils). The relative substitution of the first granulometric category is 20% to 25%, and the coefficient of saturated hydraulic conductivity $K_s < 10$ mm/h. The surface of the forested part of the catchment (88%) can be classified under Forest Hydrological Conditions (FHC) = 2, on the basis of the compactness of "forest litter" when timber understorey (TU) = 1 (depth < 5 cm).

Table 2. N-year discharges from the Bily Potok profile in the Smeda catchment, (source Czech Hydrometeorological Institute, data 2015)

Return Period (N-years)	1	2	5	10	20	50	100
Discharges Q_N ($m^3 . s^{-1}$)	21	33	54	74	97	132	162

Table 3. Curve Number (CN) for the Bily Potok profile in the Smeda catchment

Land Use	**Area %**	**Hydrol Soil Group**	**CN**	**Weighted Mean CN**
Forest	70	C	79	**55.3**
	18	B	69	**12.4**
Pastures	7	C	79	**5.5**
Arable Land	3	B	79	**2.4**
Urbanized Area	2	–	98	**1.9**
Total	**100**	**–**	**–**	**77.5**

Since 1957, three rainfall observatories have been installed: at Hejnice, at Nove Mesto and at Bily Potok. All weighted rainfall means have also been measured, together with their direct discharge flows to the Smeda River at the Bily Potok catchment outlet. The basic characteristics of the catchment were derived from geographical maps, and are presented in Figure 1. For modelling rainfall – runoff, it is important to obtain correct values of the curve numbers (CN) (NRCS 2004a, b) as the starting values for the parameters of the model: hydraulic conductivities Ks , and the sorptivity values at the field capacities Sf . The values of CN are influenced by land use. In the the Smeda catchment, the land is used mainly for forestry.

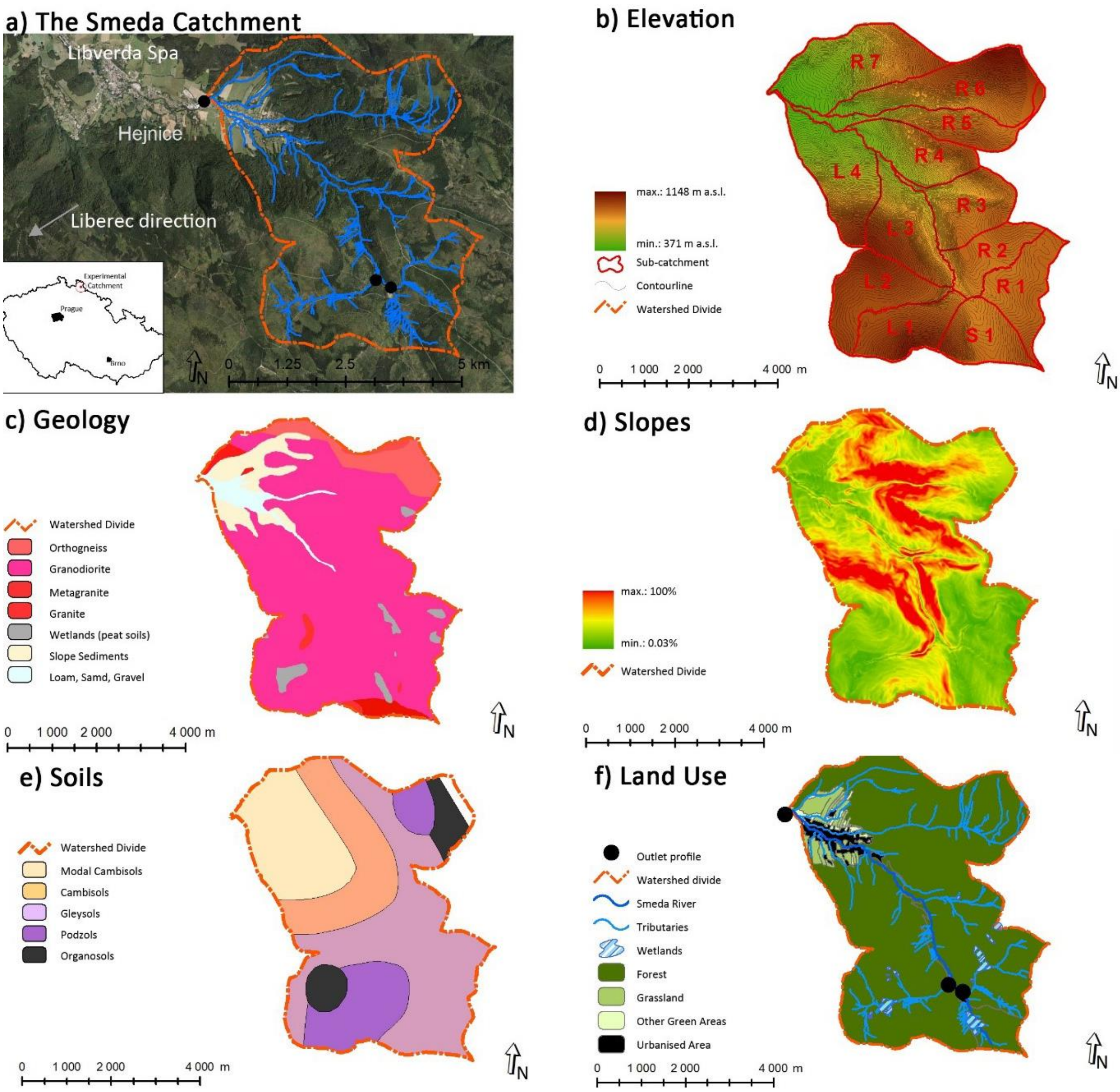

Figure 1. Selected characteristics of the Smeda catchment

In addition, we optimized the design of the terraces for the simplest one-route, or three-routes, or five-routes in parallel. For this task, just four sub-catchments were selected. Sub-catchments R5, R6, and L3, L4 were designed. Unfortunately, the water discharges of the four sub-catchments (R5, R6 and L3, L4) in urbanized areas of the village of Bily Potok reach high values, despite the five rows of terraces (Figure 2).

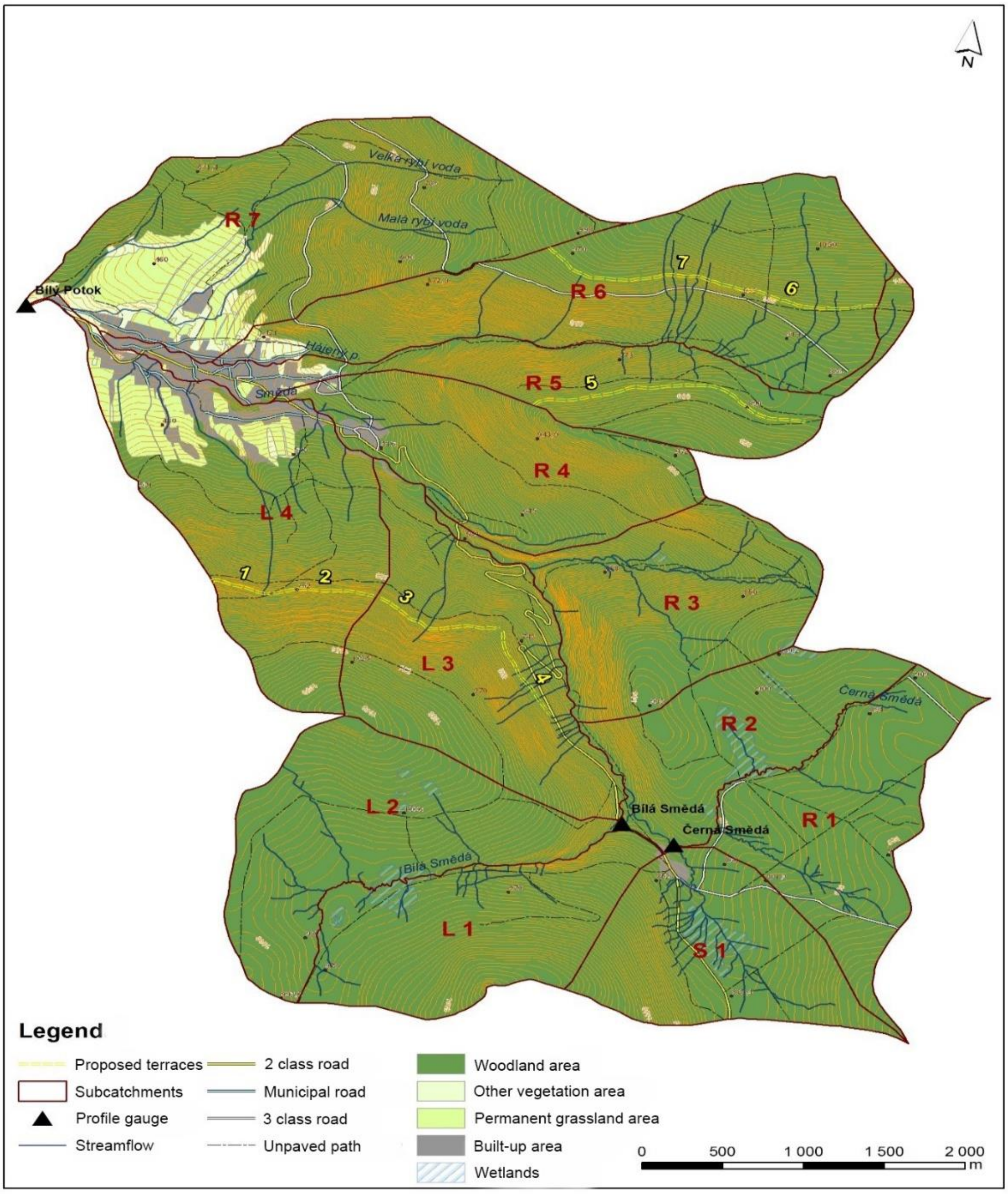

Figure 2. Design of the orderlines of each of the terraces in the Smeda catchment, sub-catchments R5, R6, L3 and L4

Table 4. Standard flood control terrace parameters in the Smeda catchment

Terrace	**Sub-catchment**	**Length**	**Entire length**	**Width**	**Slope**	**Roughness – Manning**
n	**n**	**(m)**	**(m)**	**(m)**	**(–)**	***n* (–)**
5	R5	1 794	1 794	10,0	0,01	0,150
6+7	R6	684+1 468	2 152	10,0	0,01	0,150
3+4	L3	821 + 696	1 517	10,0	0,01	0,150
1+2	L4	391 + 634	1 025	10,0	0,01	0,150
	Sum of	**lengths =**	**6 488**			

Table 4 provides the parameters of standard flood control terraces, when they are 10.0 m in width and the central part is 5.0 to 7.0 m in length, with a slight slope of 0.01 to 0.03. The total sum of the lengths of all the terraces is 6488 m. Figure 3 presents the transversal profile of the terraces. It shows the comparability between filling and excavated parts of the natural soil material.

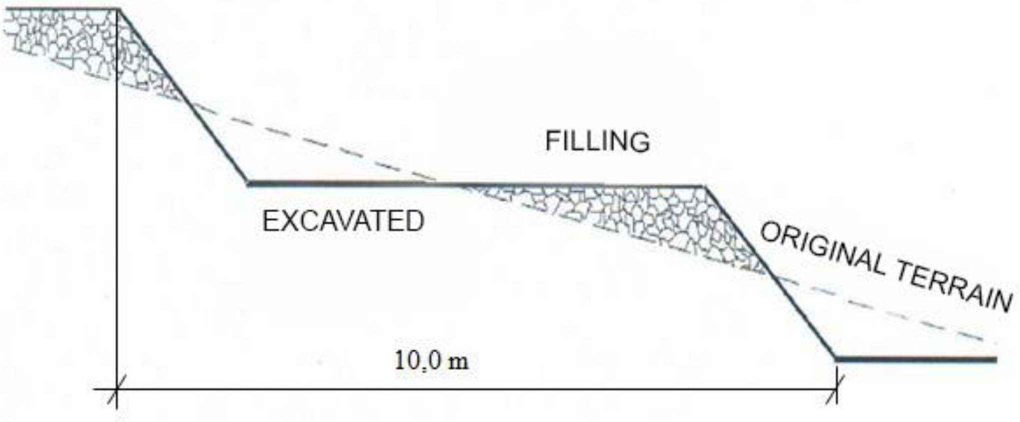

Figure 3. Transversal profile of the terraces designed for the Smeda catchment

Computations without the design of biotechnical measures were applied with short torrential rainfalls for a return period of N = 2, 10, and 100 years, and 40 min and 60 min in duration (Table 4), i.e. the conditions for which the critical culmination of the discharges was computed (N = 2 years is not printed here). The time translation of the runoff is dependent on travelling time T_L, which can be computed using the US SCS methodology (US SCS 1986, 1992), or according to Ferguson (1998), as follows:

$$T_L = (3.28 \cdot L)^{0.8} / 1900 \cdot J_0^{0.5} \qquad (1)$$

where L is hydraulic length of talweg (m), J_0 is a slope of talweg (%), A is a potential retention of the catchment (mm). For CN = 77.5 is A = 74.0 mm.

Natural gravel-bed channels are composed of heterogeneous sized grains at different spatial scales. Mao and Surian (2010) investigated sediment mobility and demonstrated the relationships between shear stress and sediment transform (Laronne & Shlomi 2007; Chang & Chung 2012). An alternative method that has been recently developed in image processing techniques has shown promising as a viable method for measuring gravel and larger size fluvial sediment (Beggan & Hamilton 2010). Hallema and Moussa (2014) used a distributed model for overland flow and channel flow based on a geomorphologic instantaneous unit hydrograph (GIUH) method. Quantification of the size distribution of fluvial gravels is an important issue in the studies of river channel behaviour in hydraulics, hydrology and geomorphology. For all the computations, we used our own DES_RAIN software (Vaššová & Kovář 2012), which is available on http://fzp.czu.cz/vyzkum/. Table 5 provides the design rainfall depths Pt,N (mm) and the duration in minutes.

Table 5. Design rainfall depths $Pt_{,N}$ (mm) and duration (min) for the Bily Potok observatory

***N* (years)**	**Design rainfall depths $P_{t,N}$ (mm) Rainfall in time *t* (min)**				
	24 h	**20‘**	**40‘**	**60‘**	**120‘**
2	66.8	27.16	32.74	35.47	40.70
5	95.0	41.37	52.07	56.40	64.65
10	113.1	51.67	65.50	70.94	81.24
20	132.0	64.04	81.90	88.71	101.52
50	155.1	79.82	103.61	112.23	128.82
100	173.2	92.15	120.00	129.98	148.91

Combining the Curve Number method and the KINFIL model. A combination of the CN method and the KINFIL model (Kovar 1989, 2014) provides a schematic representation of the Smeda catchment data for the KINFIL model (Tables 6 and 7).

Table 6. Scheme of the Smeda catchment for the KINFIL model

Cascade/ subcatchment	**Area**	**Length of basin**	**Plain**	**Area**	**Average width**	**Length**	**Slope**	**Grass land**	**Forest**	**Other area**	**Built-up area**
	(km^2)	**(km)**		**(km^2)**	**(km)**	**(km)**	**(-)**	**(%)**	**(%)**	**(%)**	**(%)**
S1	1.64	1.86	S 11	1.12	0.88	1.26	0.178	0.00	99.30	0.00	0.70
			S 12	0.53		0.60	0.114	0.00	94.60	0.00	5.40
R1	1.84	1.35	R 1	1.84	1.36	1.35	0.070	0.00	99.60	0.00	0.40
R2	1.44	0.75	R 21	0.96	1.93	0.50	0.097	0.00	99.60	0.00	0.40
			R 22	0.48		0.25	0.204	0.00	99.90	0.00	0.10
R3	1.99	1.80	R 31	1.08	1.10	0.98	0.213	0.00	100.00	0.00	0.00
			R 32	0.91		0.83	0.394	0.00	99.90	0.00	0.10
R4	1.91	1.75	R 41	0.97	1.09	0.89	0.243	0.80	91.50	0.00	7.80
			R 42	0.95		0.87	0.424	0.00	100.00	0.00	0.00
R5	1.79	0.78	R 51	0.10	2.29	0.05	0.119	0.00	100.00	0.00	0.00
			R 52	0.41		0.18	0.216	0.00	100.00	0.00	0.00
			R 53	1.27		0.56	0.269	1.10	81.10	1.70	16.10
R6	3.3	1.49	R 61	0.50	2.22	0.23	0.156	0.00	100.00	0.00	0.00
			R 62	1.33		0.60	0.218	0.00	100.00	0.00	0.00
			R 63	1.47		0.66	0.380	0.65	93.75	3.06	2.54
R7	3.46	3.50	R 71	0.40	0.99	0.41	0.180	0.00	100.00	0.00	0.00
			R 72	1.68		1.70	0.317	2.90	95.40	1.70	0.00
			R 73	1.38		1.40	0.147	34.70	42.50	15.00	7.80
L1	1.79	1.18	L 11	0.62	1.51	0.41	0.193	0.00	100.00	0.00	0.00
			L 12	1.17		0.77	0.147	0.00	99.70	0.00	0.30
L2	2.25	1.23	L 21	1.34	1.83	0.73	0.086	0.00	100.00	0.00	0.00
			L 22	0.91		0.50	0.154	0.00	99.93	0.00	0.07
L3	2.33	1.48	L 31	0.36	1.58	0.23	0.157	0.00	100.00	0.00	0.00

			L 32	1.61		1.02	0.415	0.00	98.40	0.00	1.60
			L 33	0.36		0.23	0.273	0.00	94.60	0.00	5.40
L4	2.75	2.67	L 41	0.23	1.03	0.23	0.171	0.00	100.00	0.00	0.00
			L 42	1.03		1.00	0.403	0.00	100.00	0.00	0.00
			L 43	1.49		1.45	0.164	24.70	52.00	2.00	21.30

Table 7. Correlation relationships $CN = f(K_s, S_f)$, orderlines of the terraces area

Status	**Number of lines**	**CN**	**K$_s$**	**S$_f$**	**Terraces area**	
		–	mm.h^{-1}	mm	km^2	%
Without terraces	–	77	1.86	22.60	–	–
With terraces	1	75	2.02	20.75	0.423	1.61
	3	71	3.63	18.34	1.270	4.86
	5	67	5.20	16.60	2.120	8.11

The current version of the KINFIL model is based on the Green-Ampt infiltration theory, with ponding time according to Mein and Larson (1973) and Morel-Seytoux (Morel-Seytoux & Verdin 1981; Morel-Seytoux 1982; Ponce & Hawkins 1996):

$$K_S\left(z_f + H_f/z_f\right) = (\theta_s - \theta_i)\, dz_f/dt \qquad (2)$$

$$S_f = (\theta_s - \theta_i) \cdot H_f \qquad (3)$$

$$t_p = S_f/i \cdot \left(\frac{i}{K_S} - 1\right) \qquad (4)$$

Where K_s is the hydraulic conductivity (m·s^{-1}); z_f is the vertical extent of the saturated zone (m); θ_s is the water content at natural saturation (-); θ_i is the initial water content (-); H_f is the wetting front suction (m); i is the rainfall intensity (m·s^{-1}); S_f is the storage suction factor (m); t_p is the ponding time (s), and t is the time (s).

The main task is to assess hydraulic conductivity Ks , and the storage suction factor Sf (at field capacity, FC). These two parameters can be measured directly on small experimental catchments. In larger catchments, the previously derived relationships of these parameters and the CN, which are widely used by Soil Conservation Service (SCS) (US SCS 1986), can also be applied. The Curve Numbers corresponds with conceptual values of soil parameters K_s and S_f *(FC)*: $CN=f(K_s, S_f)$.

The CN method, developed by the US Soil Conservation Service based on soil types (Brakensiek & Rawls 1981), design rainfall depths and duration, vegetation cover, land use, and antecedent moisture conditions, is widely used due to its easy application. An evident shortcoming of this methodology is that it disregards both the intensity and the duration of the rainfall that causes flood runoff. This imperfection can be dealt with by using the physically-based infiltration approach of the KINFIL model (Kovář 1992) instead of the usual empirical CN approach. The relationships between the CN method and the soil type parameters have been used for the infiltration process. These relationships were derived by correlating the data from 62 gauges located in the Czech territory (Šamaj et al. 1983; Kovář 1992) and the parameters of the basic soil groups.

RESULTS AND DISCUSSION

The computed CN values for the Smeda catchment are shown in Table 8.

Table 8. Curve Number (CN) values derived from the Smeda catchment for the soil types (US classification and Czech Bily Potok major profile)

Profile	**US Soil types (Brakensiek and Rawls (1981), can be amended with Czech soil classification by Novak)**									
Bily Potok - CN values:	1	2	3	4	5	6	7	8	9	10
	95.1	92.1	90.0	86.8	85.8	78.0	64.1	60.7		

Table 9 shows the principles for computing the results from the correlation processes to change the hydraulic conductivity K_s ($\mathrm{mm \cdot h^{-1}}$) and the sorptivity $S(\theta_{FC})$ ($\mathrm{mm \cdot h^{-0.5}}$ at field capacity). When this sorptivity $S(\theta_{FC})$ can be amended to the storage suction factor, its form can be expressed as follows:

$$S_f = (s(\theta_{FC})^2 / 2.0 \cdot K_S) \tag{5}$$

Table 9. Instruction from the correlation processes for the hydraulic conductivity K_s ($\mathrm{mm \cdot h^{-1}}$) and the storage suction factor S_f (mm)

Conditions for CN	K_s equations ($mm \cdot h^{-1}$)	Accuracy
if CN ≥ 75:	$K_S = \frac{100 - CN}{12 \cdot 4}$	σ = 0.084
if 74 ≥ *CN < 36:*	$K_S = 31.4 - (0.39 \cdot CN)$	σ = 0.136
if CN < 35:	$K_s = 47.1 - (0.82 \cdot CN)$	
Conditions for CN	$S(\theta_{FC})$ **equations** ($mm \cdot h^{-0.5}$)	
if CN > 65:	$S(\theta_{FC}) = \frac{100 - CN}{2.5}$	
if CN < 64:	$S(\theta_{FC}) = 30.25 - (0.15 \cdot CN)$	
NOTE:	$S_f = S(\theta_{FC})^2/2.0 \cdot K_S$: storage suction factor (mm)	

The second part of the KINFIL model simulates propagation and transformation of direct runoff (Beven 2006). The partial differential equation describes unsteady flow approximated by kinematic wave on a cascade of planes that arranged according to the topography of the catchment:

$$\frac{\partial y}{\partial t} + \alpha m y^{m-1} \cdot \frac{\partial y}{\partial x} = i_e(t) \qquad (6)$$

Where *x, y* and *t* are the lenght, depth and time (m, m, s), respectively *α* and *m* are hydraulic parameters, and $i_e(t)$ is the excess rainfall intensity ($m \cdot s^{-1}$). This equation is solved by finite-difference method using an explicit numerical scheme. Numerical stability of the scheme is ensured if the time and space step is according to equation (7):

$$c \frac{\Delta t}{\Delta x} \leq 1 \qquad (7)$$

Where *c* is celerity, $c = m \cdot y^{m-1}$, *y* is water depth.

Explicit schemes in the software, where is only one unknown on the left side of equation are quick but sensitive on the stability of computation if there is higher difference in time *(Δt)* and space step *(Δx)*, (see equation 7).

To ensure safe biotechnical measures, it is necessary to construct multiple terraces in a contour line system. In the Smeda basin, one row 10 m in width has been built in four sub-catchments R5, R6, and L3, L4. For a greater level of safety, the Bily Potok municipality will need at least five rows of terraces to decrease the water discharges for N = 10-year flood from 67.0 m^3/s (without terraces) to about 64.5 m^3/s. The Tables 10−13 and Figures 4 and 5 provide results that reduce the cumulation of N =100-year discharges from 167.3 m^3/s (without terraces) to about 162.0 m^3/s. The most dangerous time situation is duration of 40 min. A similar computation was also performed for a torrential rain of 60 min in duration, but this is a less dangerous scenario.

Table 10. Maximum N = 10 years and N = 100 years discharges with duration 40 min, without terraces and with 5 rows of terraces.

		10 years		**100 years**	
Sequence	**Time, hours**	**Q – without teraces, m^3/s**	**Q - 5 rows of terraces, m^3/s**	**Q – without terraces, m^3/s**	**Q - 5 rows of terraces, m^3/s**
1	0.333	4.461	4.252	19.226	17.906
2	0.666	20.023	18.913	69.224	64.570
3	1.000	42.347	40.005	129.138	123.765
4	**1.333**	**67.069**	**64.454**	**167.356**	**161.927**
5	1.666	53.926	52.618	105.956	103.828
6	2.000	38.737	38.091	67.480	66.622
7	2.333	27.635	27.296	44.925	44.524
8	2.666	20.400	20.205	30.333	30.117
9	3.000	15.540	15.419	20.845	20.715
10	3.333	12.181	12.101	14.843	14.759
11	3.666	9.580	9.524	10.963	10.905
12	4.000	7.507	7.466	8.332	8.290
13	4.333	5.920	5.889	6.476	6.444
14	4.666	4.735	4.711	5.127	5.103
15	5.000	3.843	3.824	4.125	4.106
16	5.333	3.164	3.149	3.368	3.353
17	5.666	2.643	2.631	2.789	2.776
18	6.000	2.235	2.225	2.339	2.329
19	6.333	1.909	1.900	1.983	1.974
20	6.666	1.644	1.637	1.698	1.690
21	7.000	1.427	1.421	1.466	1.460
22	7.333	1.248	1.242	1.275	1.269
23	7.666	1.097	1.092	1.117	1.112

24	8.000	0.970	0.966	0.985	0.981
25	8.333	0.862	0.858	0.874	0.870
26	8.666	0.769	0.766	0.779	0.776
27	9.000	0.690	0.687	0.699	0.696
28	9.333	0.622	0.619	0.629	0.626
29	9.666	0.563	0.561	0.569	0.567
30	10.000	0.512	0.510	0.517	0.515

Table 11. Effectiveness of the terraces in the Smeda catchment, N = 10 and 100 years, time duration t_d = 40 and 60 min (effective rainfall; 5 rows of terraces)

EFFECTIVE RAINFALL	
Without terraces	**With terraces**
N = 10, TD = 40´: RER = 56.7 mm	RER_T = 55.9 mm
N = 10, TD = 60´: RER = 59.7 mm	RER_T = 58.7 mm
N = 100, TD = 40´: RER = 112.2 mm	RER_T = 110.4 mm
N = 100, TD = 60´: RER = 118.8 mm	RER_T = 117.8 mm

Table 12. Discharges from individual subcatchments of the Smeda catchment, N = 10 years of 40 min time duration

S1-2	R1-1	R2-2	R3-2	R4-2	R5-3	R6-3	R7-3	L1-2	L2-2	L3-3	L4-3
0.201	0.244	0.296	0.234	0.241	0.802	0.464	0.257	0.393	0.487	0.559	0.282
0.932	1.128	1.380	1.083	1.113	3.704	2.146	1.190	1.815	2.248	2.041	1.243
2.006	2.516	3.735	2.410	2.491	7.061	4.890	2.654	4.085	4.549	3.979	1.971
2.884	4.334	5.836	3.958	4.863	7.460	10.448	4.548	6.985	7.155	6.578	2.021
2.453	4.199	3.802	3.407	5.417	3.675	9.522	4.253	4.619	5.718	5.954	0.908
2.220	3.615	2.227	3.079	4.055	1.788	6.475	3.726	2.856	3.864	4.434	0.398
2.116	2.717	1.327	2.810	2.700	0.937	4.184	3.431	1.753	2.535	2.932	0.194
1.820	1.923	0.824	2.407	1.828	0.538	2.772	3.375	1.104	1.701	2.003	0.106
1.446	1.365	0.537	1.875	1.264	0.334	1.889	3.456	0.727	1.174	1.409	0.065
1.115	0.994	0.368	1.436	0.904	0.222	1.336	3.418	0.501	0.835	1.011	0.042
0.860	0.743	0.262	1.103	0.664	0.155	0.975	3.075	0.359	0.612	0.741	0.029
0.673	0.569	0.194	0.862	0.500	0.113	0.732	2.557	0.266	0.461	0.558	0.021
0.534	0.444	0.148	0.686	0.388	0.086	0.565	2.066	0.203	0.356	0.429	0.016
0.431	0.353	0.115	0.554	0.307	0.066	0.445	1.675	0.159	0.280	0.337	0.012
0.353	0.285	0.092	0.453	0.246	0.053	0.356	1.373	0.127	0.225	0.270	0.010
0.293	0.234	0.074	0.376	0.200	0.043	0.289	1.141	0.103	0.184	0.219	0.008
0.245	0.195	0.061	0.315	0.165	0.035	0.239	0.964	0.085	0.152	0.181	0.006
0.207	0.165	0.051	0.267	0.138	0.029	0.200	0.823	0.070	0.127	0.151	0.005
0.177	0.140	0.043	0.228	0.117	0.025	0.170	0.709	0.059	0.108	0.128	0.005
0.153	0.121	0.037	0.196	0.101	0.021	0.145	0.615	0.051	0.092	0.110	0.004
0.133	0.105	0.032	0.170	0.087	0.018	0.125	0.537	0.043	0.080	0.095	0.003
0.116	0.091	0.028	0.148	0.076	0.016	0.109	0.471	0.038	0.070	0.083	0.003
0.102	0.080	0.024	0.131	0.066	0.014	0.095	0.416	0.033	0.061	0.073	0.003
0.091	0.070	0.021	0.116	0.058	0.012	0.084	0.368	0.029	0.054	0.064	0.002
0.081	0.062	0.019	0.103	0.051	0.011	0.074	0.327	0.026	0.048	0.057	0.002
0.072	0.055	0.017	0.093	0.046	0.009	0.066	0.292	0.023	0.043	0.051	0.002
0.065	0.050	0.015	0.083	0.041	0.008	0.059	0.263	0.021	0.038	0.045	0.002
0.059	0.044	0.014	0.075	0.037	0.008	0.054	0.237	0.019	0.035	0.041	0.001
0.053	0.040	0.012	0.068	0.033	0.007	0.048	0.215	0.017	0.031	0.037	0.001
0.048	0.036	0.011	0.062	0.030	0.006	0.044	0.196	0.015	0.028	0.033	0.001

Table 13. Discharges from individual subcatchments of the Smeda catchment, N = 100 years of 40 min time duration

S1-2	R1-1	R2-2	R3-2	R4-2	R5-3	R6-3	R7-3	L1-2	L2-2	L3-3	L4-3
0.877	1.062	1.287	1.019	1.048	3.493	2.020	1.121	1.709	2.120	2.317	1.153
3.268	4.008	5.767	3.844	3.957	12.294	7.670	4.228	6.468	7.571	6.486	3.664

5.556	8.368	11.138	7.618	9.490	14.215	20.231	8.777	13.384	13.496	12.711	3.954
8.380	13.102	11.455	11.178	15.085	14.356	26.099	13.347	14.083	17.831	18.556	3.884
6.945	9.489	6.230	9.571	9.879	5.669	16.535	11.851	7.712	9.868	10.862	1.347
5.391	5.927	3.123	7.031	6.118	2.305	9.584	11.081	4.091	5.736	6.605	0.488
3.757	3.734	1.657	4.863	3.647	1.089	5.539	10.776	2.220	3.401	4.026	0.216
2.600	2.432	0.955	3.363	2.274	0.590	3.374	8.705	1.295	2.104	2.527	0.114
1.844	1.642	0.595	2.386	1.484	0.355	2.181	6.457	0.811	1.370	1.653	0.067
1.341	1.151	0.396	1.732	1.014	0.232	1.487	4.837	0.541	0.937	1.130	0.044
1.000	0.837	0.277	1.289	0.724	0.161	1.058	3.735	0.379	0.668	0.804	0.030
0.762	0.626	0.203	0.981	0.535	0.116	0.780	2.942	0.277	0.494	0.593	0.022
0.594	0.481	0.153	0.764	0.407	0.087	0.592	2.347	0.209	0.376	0.450	0.016
0.472	0.377	0.118	0.606	0.318	0.067	0.461	1.890	0.162	0.293	0.350	0.012
0.382	0.301	0.094	0.489	0.254	0.053	0.366	1.537	0.129	0.233	0.278	0.010
0.313	0.245	0.076	0.401	0.206	0.043	0.297	1.263	0.104	0.189	0.225	0.008
0.260	0.202	0.062	0.332	0.170	0.035	0.244	1.051	0.086	0.156	0.185	0.006
0.219	0.169	0.052	0.279	0.142	0.029	0.204	0.885	0.071	0.130	0.154	0.005
0.186	0.143	0.044	0.237	0.119	0.025	0.172	0.753	0.060	0.110	0.131	0.005
0.159	0.123	0.037	0.203	0.102	0.021	0.147	0.646	0.051	0.094	0.112	0.004
0.137	0.106	0.032	0.175	0.088	0.018	0.126	0.558	0.044	0.081	0.097	0.003
0.119	0.093	0.028	0.153	0.076	0.016	0.110	0.485	0.038	0.070	0.084	0.003
0.105	0.081	0.024	0.134	0.067	0.014	0.096	0.425	0.033	0.061	0.074	0.003
0.092	0.072	0.021	0.118	0.059	0.012	0.084	0.375	0.029	0.054	0.066	0.002
0.082	0.064	0.019	0.105	0.052	0.011	0.075	0.332	0.026	0.048	0.058	0.002
0.073	0.057	0.017	0.094	0.046	0.009	0.067	0.296	0.023	0.043	0.052	0.002
0.066	0.052	0.015	0.084	0.041	0.008	0.060	0.265	0.021	0.038	0.047	0.002
0.059	0.047	0.014	0.076	0.037	0.007	0.054	0.239	0.019	0.034	0.042	0.001
0.054	0.042	0.012	0.069	0.034	0.007	0.049	0.216	0.017	0.031	0.038	0.001
0.049	0.038	0.011	0.063	0.031	0.006	0.044	0.197	0.015	0.028	0.034	0.001

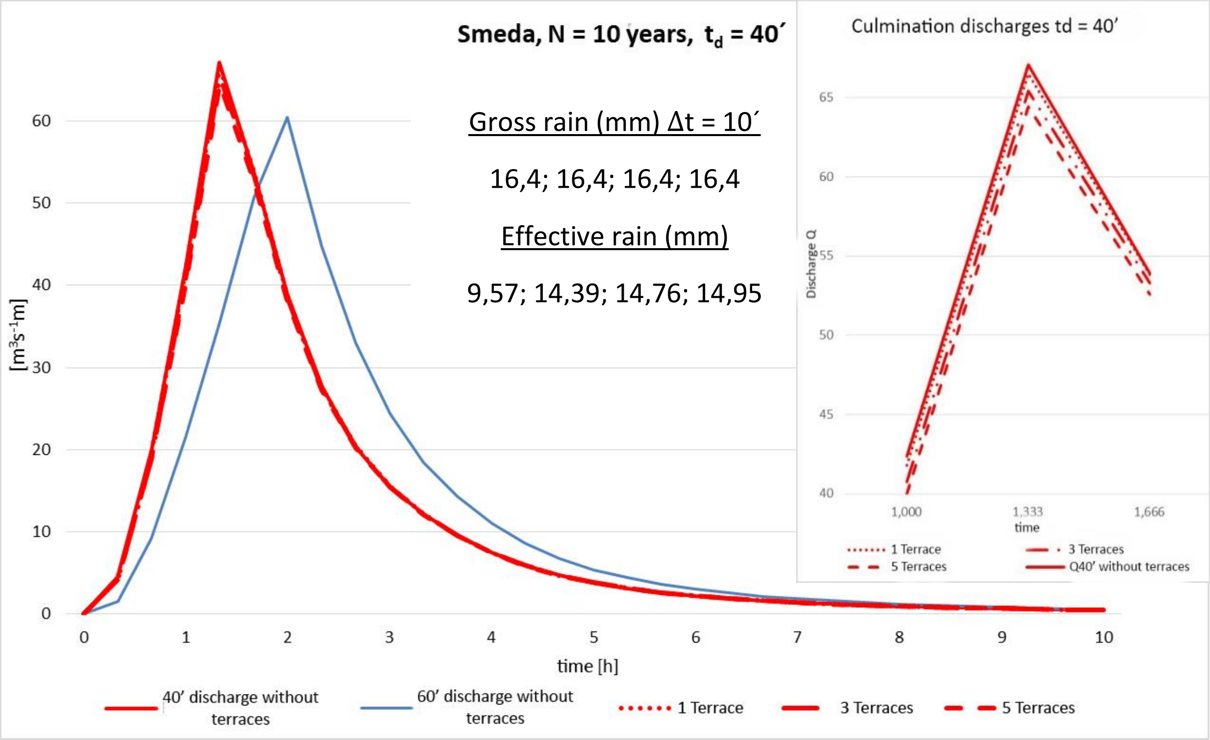

Figure 5. Smeda, N = 10 years, t_d = 40 min. Discharges without terraces, 1 terrace, 3 terraces, 5 terraces

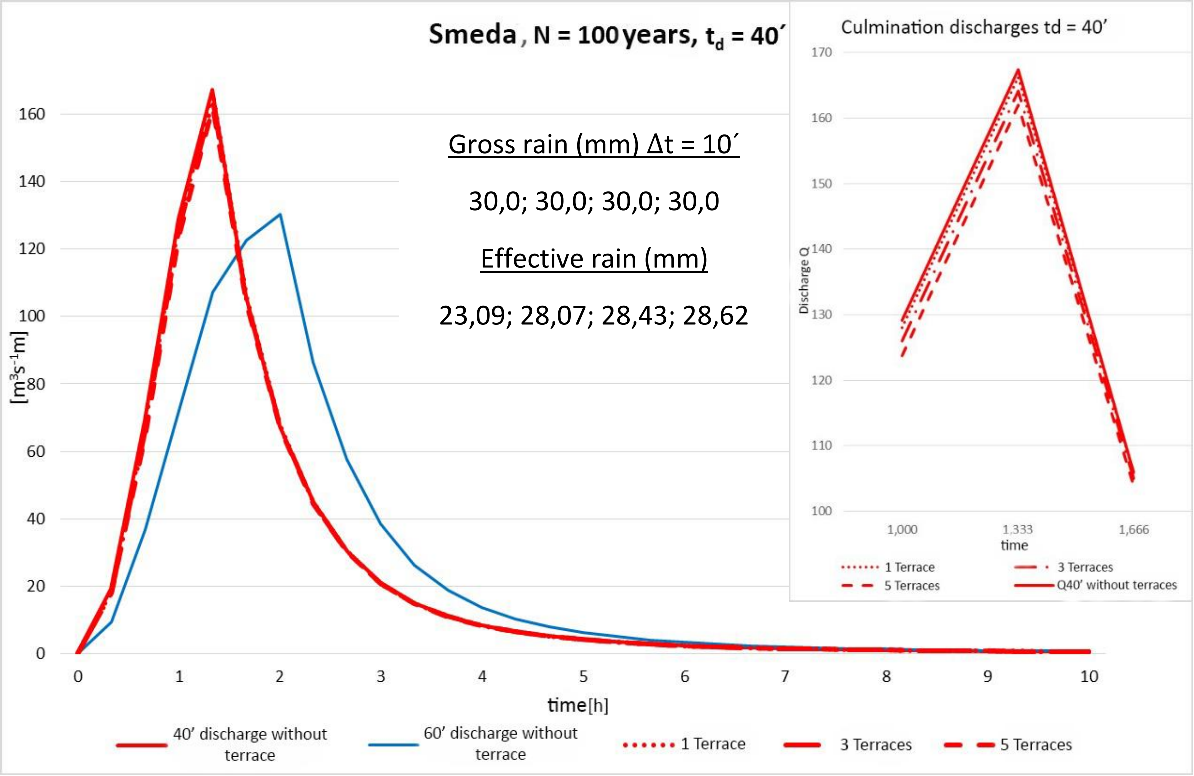

Figure 6. Smeda, N = 100 years, td = 40 min. Discharges without terraces, 1 terrace, 3 terraces, 5 terraces.

For a comparison with the N-year discharges on the Smeda catchment, we computed Tables and Figures with geometric factors for sub-catchments and their land use. The same procedure was followed, in principle, for N = 2 years and 40 min duration. However, this computation is not presented here.

CONCLUSION

Slope terraces have hydro-physical characteristics that can be different and they require a lot of finances. Hydrological analyses indicate that the use of flood control terraces as biotechnical measures does not provide any effective barriers for the Bily Potok municipality. For a practical application, more than four sub-catchments are needed. In addition, more than five rows of terraces are needed, and also at least two polders. The provision of effective measures will require more investment than is currently envisaged. A comparison of the computational results (Table 10) shows that correct results are dependent on regular maintenance.

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The Use of Snyder Synthetic Hydrograph for Simulation of Overland Flow in Small Ungauged and Gauged Catchments

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ABSTRACT

The paper presents the results of simulated overland flow on the Třebsín experimental area, Czech Republic, using the Snyder synthetic unit hydrograph. In this research an attempt was made to discover a new approach to overland flow simulation that could give precise results like the KINFIL model for a small ungauged catchment. The provided results also include a comparison with the KINFIL model for N = 10, 20, 50 and 100 year recurrence of rainfall-runoff, with the rainfall time duration td = 10, 20, 30, and 60 min. Concerning a small gauged catchment, one of the most accurate and elegant methodologies, Matrix Inversion Model, can be used for the measurement of both the gross rainfall and the runoff. This method belongs to a matrix algebra concept. For the sake of completeness, we designated this model at the end of the present article to show how exact this forward march can be.

Keywords: extreme rainfall; infiltration intensity; KINFIL model; Matrix Inversion Model; Snyder unit hydrograph

INTRODUCTION

One of the main problems in hydrological studies is the prediction of runoff from an ungauged basin, since the majority of small catchments are ungauged (Hrachowitz et al. 2013). The data on rainfall events are often available for such basins, however the simulation of runoff is much more complicated than for the basins with well observed data of runoff discharges. In addition, it is even more sophisticated for the small ungauged catchments (Parajka et al. 2013). There are many different approaches to the solution of such a hydrological riddle. In 1932 the unit hydrograph method was introduced by Sherman (1932) and changed the runoff-rainfall modelling forever. It has become the most widely used method of flood analysis for gauged basins. In spite of obvious advantages, simplicity and applicability of this method, it has one big imperfection: it cannot be used on the basins with lack of data. For the extension of the unit hydrograph theory for ungauged basins the synthesis from physical characteristics should be considered as an effective and necessary measure. Currently, there exist several methods for developing the synthetic unit hydrograph using measurable physical basin characteristics. As the founder of the unit hydrograph theory, Sherman was the first to study the possibilities of developed method extension. The physical characteristics of the basin he thought to have an impact on the hydrograph and possibly could be used for the estimation of runoff on the ungauged basins are: the shape and size of the drainage area, slopes of valley sides and mainstream, distribution of water channels and ponding due to course or surface obstacles. As the basis of most synthetic unit hydrograph methods researchers still use Sherman's ideas. Major part of the methods try to find relationships between physical basin parameters and unit hydrograph characteristics, the differences are in the used methodologies or in recognized relationships (Ellouze-Gargouri & Bargaoui 2012; Singh et al. 2014; Rigon et al. 2016). Those methods for developing a synthetic hydrograph for ungauged areas have been made by Bernard (1935), Snyder (1938), McCarthy (1939) and Clark (1945). The final step of our study was a Matrix Inversion Model calculation. The basics of this methodology were developed by Snyder (1961), through the concepts of matrices and vectors. The convolution of excess rainfall with the T-hour Unit Hydrograph (TUH) is simply the process of multiplication of a matrix by a vector. The present study was conducted in the Třebsín experimental area. The surface runoff simulation was done using two different approaches: Snyder synthetic unit hydrograph method and kinematic wave based on the KINFIL model.

MATERIAL AND METHODS

This paper describes the continuation of research outcomes from the article published by Fedorova et al. (2017), using the HEC-HMS SCS Unit Hydrograph and KINFIL model to compute the surface runoff from extreme rainfall in the small ungauged Knínice catchment. One of the articles mentioning the unit hydrograph was published by Černohous and Kovář (2009) due to approximation of the recession limb of the hydrograph. The KINFIL model is currently used for simulating erosion processes and for predicting the vulnerability of soil to water, since the surface runoff and water erosion are closely related. In the calculation, we designed rainfall events on experimental plots No. 4 and 5 in Třebsín, which are located about 40 km from Prague in south-east direction, close to the village of Třebsín. The location of Experimental Runoff Area (ERA) is depicted in Figure 1.

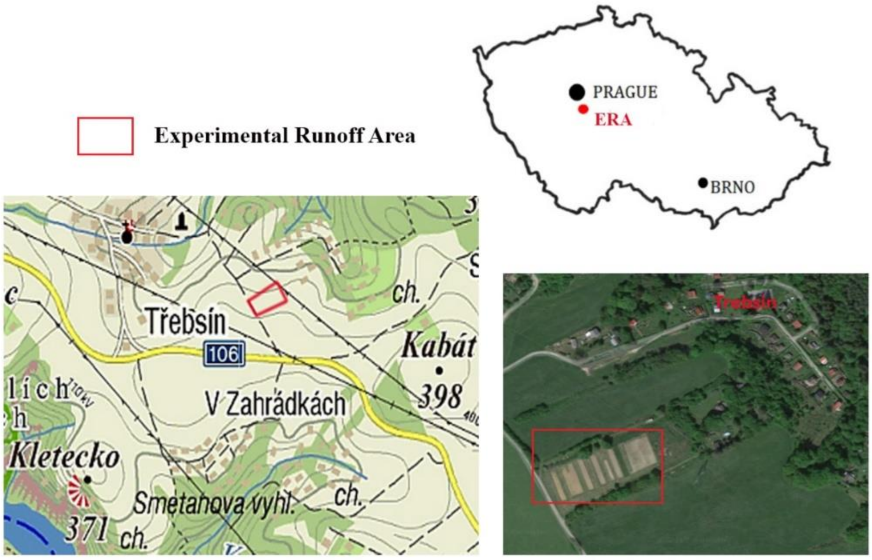

Figure 1. The location of the Experimental Runoff Area (ERA)

In sum, there are nine experimental plots, the length of each is 36 m and the width is 7 m. The average slope of the experimental area is about 7°. The research location is operated by the Research Institute for Soil and Water Conservation in Prague-Zbraslav (RISWC Prague). The area belongs to a mildly warm region, with annual mean precipitation of 517 mm, average temperature of 6.5°C and an altitude of 340–350 m a.s.l. The natural soil composition is originally a gneiss substrate and is mostly of Haplic Cambisol type, belonging to the soil group of silty loam. The scheme of experimental runoff plots is presented in Figure 2. The studied plots are highlighted in green colour.

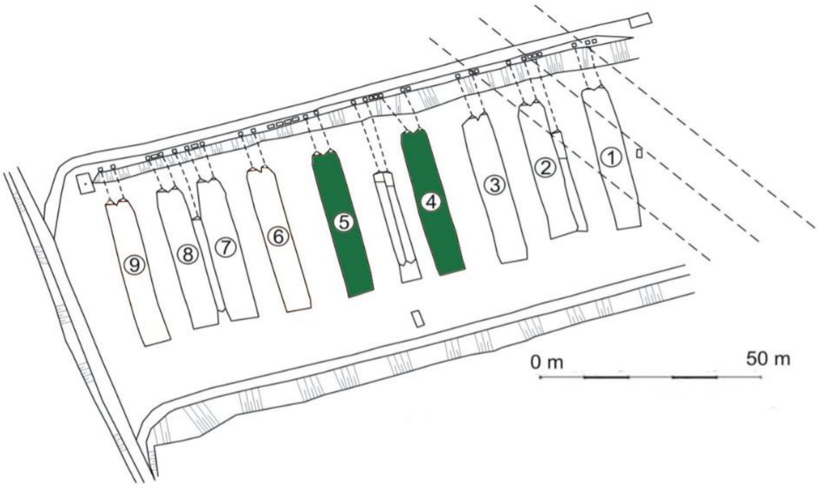

Figure 2. The scheme of runoff plots

The rainfall data

The rainfall data from the Benešov station was used for runoff simulation in the Třebsín catchment. This rain gauge provides daily rainfall data with a return period N = 2, 5, 10, 50 and 100 years. Due to the small catchment area, the selected periods of critical rainfall time duration are t_d = 20, 30 and 60 min and the return period of N = 10, 20, 50 and 100 years. To compute the reduction in the daily rainfall depths $P_{t,N}$ was used the DES_RAIN procedure (http://fzp.czu.cz/vyzkum) (Vaššová and Kovář 2011). The procedure is based on regional parameters a and c, derived by the methodology of Hrádek and Kovář (1994). The results are provided in Table 1.

Table 1. Maximum rainfall depths $P_{t.N}$ on the Benešov station (mm)

N	***P**$_{t.N}$*	***t* (min)**			
(years)	(mm)	**10′**	**20′**	**30′**	**60′**
2	38.6	12.8	15.7	17.7	20.5
5	52.9	18.6	23.0	26.1	31.4
10	62.0	22.3	28.3	32.6	38.9
20	71.6	27.2	34.7	40.1	48.1
50	83.3	33.4	42.9	49.7	60.3
100	92.4	37.9	49.2	57.2	69.3

The field measurements

The average values for saturated hydraulic conductivity K_s (mm/min) and for sorptivity S (mm/min$^{0.5}$) were obtained by the infiltrometer method (double cylinders).

The Richards equation (Kutílek and Nielsen 1994) combined with Philip solution for non-steady flow infiltration (Philip 1957) was implemented for calculation of hydraulic soil parameters . The simplified Philip equation for the infiltration intensity v_f calculated with the saturated hydraulic conductivity K_s (m/s) and sorptivity S (m/s^{0,5}), is as follows:

$$v_f\ (t) = \frac{1}{2}\ S\ .\ t^{-1/2} +\ K_s \qquad (1)$$

Subsequently, parameters K_s and S were both computed, applying the method of the non-linear regression (Kovář et al. 2011, Štibinger 2011). Table 2 provides the measured hydraulic conductivity K_s, sorptivity S, and the storage suction factor S_f (mm):

$$S_f = \frac{S^2}{2K_s} \qquad (2)$$

Table 2. The soil hydraulic parameters: hydraulic conductivity K_s (mm/min), sorptivity S (mm/min$^{0.5}$), and storage suction factor S_f (mm)

Plot	**Sorptivity S, (mm/min$^{0.5}$)**	**Saturated hydraulic conductivity K$_s$, (mm/min)**	**Storage suction factor S$_f$, (mm)**
4	4.64	4.36	2.47
5	4.13	1.65	5.17

Snyder Unit Hydrograph

The unit hydrograph is a universal solution for any basin rainfall-runoff relationship providing the single storm hydrograph parameters given the excess rainfall data. However, major part of watersheds have no recorded rainfall or runoff data. The answer is in synthesizing of unit hydrograph - estimating the simple rainfall-runoff relationship by application of physical parameters of drainage basin.

In the year 1938, a concept of the synthetic unit hydrograph was introduced by Snyder. The methodology is based on the detailed and structured analysis of a large number of hydrographs from different catchments in the Appalachian region. The study led to the following formula (3) for time lag (Ponce 1989):

$$T_{lag} = C_t(LL_c)^{0,2} \qquad (3)$$

where: T_{lag} is catchment time lag in hours, C_t is coefficient explaining catchment gradient and related to catchment storage, L is the mainstream length (km), Lc is the mainstream length from outlet to the closest point to catchment centroid (km).

Snyder’s formula for peak discharge is as follows (Ponce 1989):

$$Q_p = \frac{2,78 \cdot C_p \cdot A}{T_{lag}} \qquad (4)$$

Where Q_p is a peak discharge related to 1 cm of effective rainfall (m^3/s), A is a catchment area (km^2), C_p is empirical coefficient connected with triangular base time to time lag.

KINFIL rainfall-runoff model

The KINFIL model is used for simulation of significant rainfall-runoff events or for estimation of design discharge in catchments that are impacted by human activities. The kinematic wave techniques are generally considered to be sufficient for analysis of overland and channel flow. This method is a simplified version of the dynamic wave theory.

Current version of presented model consists of two parts. First part is based on Green-Ampt infiltration theory with ponding time according to Mein and Larson (1973) and Morel-Seytoux (Morel-Seytoux and Verdin 1981, Morel-Seytoux 1982):

$$K_S(z_f + H_f/z_f) = (\theta_s - \theta_i)\, dz_f/dt \qquad (5)$$

$$S_f = (\theta_s - \theta_i) \cdot H_f \qquad (6)$$

$$t_p = S_f/i \cdot \left(\frac{i}{K_S} - 1\right) \qquad (7)$$

Where K_s is hydraulic conductivity (m·s^{-1}); z_f is the vertical extent of the saturated zone (m); θ_s is the water content at natural saturation (-); θ_i is the initial water content (-); H_f is the wetting front suction (m); i is the rainfall intensity (m·s^{-1}); S_f is the storage suction factor (m); t_p is ponding time (s), and t is time (s). On small experimental catchments the hydraulic conductivity K_s and the storage suction factor S_f can be measured directly.

The overland flow part of the model uses the kinematic equation and can be described by Eq.(8) (Kibler and Woolhiser 1970, Beven 2006):

$$\frac{\partial y}{\partial t} + \alpha . m . y^{m-1} . \frac{\partial y}{\partial x} = r_e(t) \qquad (8)$$

where r_e (t) is rainfall excess intensity (m/s), y, t, x are ordinates of the depth of water, time and position (m, s, m), and α, m are hydraulic parameters.

Matrix Inversion Model

One of the most accurate mathematical model for known rainfall and runoff parameters is the Matrix Inversion Model. The basic processes of this method have been developed in Tennessee Valley Authority study by Snyder (1961). The detailed view if the process involved in the convolution of discrete values of TUH with the rainfall excess to produce the direct runoff through summation provides Equation 9 (O'Donnell 1960):

$$Q_{m+n-1} = \Delta T * \sum_1^{m+n-1} P_m * U_{m-n} \qquad (9)$$

Where Q is the runoff, P is a rainfall, U is the unit hydrograph ordinates, m is a number of rainfall intervals, n is the number of isochrones areas (equals to number of TUH ordinates), ΔT is a length of time period. When $\Delta T \rightarrow 0$, then summation can be replaced by a Duhamel's convolution integral:

$$Q(t) = \int_0^t P(\tau) * U(t-\tau) d\tau \qquad (10)$$

Equation 9 shows that basically the process is a multiplication of a matrix by a vector. However, this means to solve *m+n-1* equals of *n* unknown values TUH. Consequently, it is an overdetermined system of m–1 equations and it can hardly be solved by the substitution method. This computation suits the matrix algebra very well (Figure 3):

$$Q_1 = P_1 * U_1 \quad + \quad 0 \quad + \quad 0 \ldots\ldots\ldots \ldots\ldots\ldots\ldots\ldots \; +0 \; + 0$$

$$Q_2 = P_2 * U_1 + P_1 * U_2 + 0 \ldots . + \quad 0 \ldots\ldots\ldots\ldots\ldots \; +0 \; + 0$$

$$Q_3 = P_3 * U_1 + P_2 * U_2 + P_1 * U_3 + 0 \ldots + \quad 0 \ldots \ldots +0 \; + 0$$

$$Q_m = P_m * U_1 + P_{m-1} * U_2 + P_{m-2} * U_3 + \cdots + P_1 * U_m + 0$$

$$Q_{m+1} = 0 \quad + P_m * U_2 + P_2 * U_m + \cdots\cdots + P_1 * U_{m+1} + 0$$

$$Q_{m+n-1} = 0 \quad + \quad 0 \quad + \quad 0 \; + \; 0 \quad + \cdots\cdots\cdots + P_m * U_n$$

Figure 3. The group of equations relating rainfall and unit hydrograph ordinates to runoff.

The matrix equivalent of the equations of Figure 3 is given by Figure 4:

$$\left|\begin{array}{cccccccccc}
X_1 & 0 & 0 & 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & & & & & & & 0 \\
X_2 & X_1 & 0 & 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & & & & & & 0 \\
X_3 & X_2 & X_1 & 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & & & & & & 0 \\
\vdots & & & & & & & & & \vdots \\
\vdots & & & & & & & & & \vdots \\
X_m & X_{m-1} & X_{m-2} \ldots\ldots & X_1 & 0 & 0 & 0 \ldots\ldots\ldots\ldots & & & 0 \\
0 & X_m & X_{m-1} \ldots\ldots & X_2 & X_1 & 0 & 0 \ldots\ldots\ldots\ldots & & & 0 \\
\vdots & & & & & & & & & \vdots \\
\vdots & & & & & & & & & \vdots \\
0 & 0 & 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & & & & & 0 & X_m & X_{m-1} \\
0 & 0 & 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & & & & & 0 & 0 & X_m
\end{array}\right| * \left|\begin{array}{c} U_1 \\ U_2 \\ U_3 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ U_n \end{array}\right| = \left|\begin{array}{c} Y_1 \\ Y_2 \\ Y_3 \\ \vdots \\ \vdots \\ Y_m \\ Y_{m+1} \\ \vdots \\ \vdots \\ \vdots \\ Y_{m+n-1} \end{array}\right|$$

Figure 4. Matrix equivalent of discrete convolution equations.

The matrix technique suggested in the abovementioned T.V.A study (Snyder 1961) automatically provides a least-squares solution to TUH ordinates. Precipitation P should be replaced by the letter X (only for rainfall, e.g. liquid form of precipitation); Q by the letter Y for discharge and the usual notation, the matrix equation can be written:

$$|X| * |U| = |Y| \qquad (11)$$

To solve the Equation 11 for $|'U|$, one must first make the rectangular matrix $|'X|$ a square one. This can be done by multiplying both sides of Equation 11 by the transpose of $|X|^T$ left side, which is the matrix formed by interchanging the rows and columns of $|X|$ in Equation 12:

$$|X|^T * |X| * |U| = |Z| * |U| = |X|^T * |Y| \qquad (12)$$

Where:

$$|X|^T * |X| = |Z| \qquad (13)$$

$$|A| = |X|^T * |Y| \qquad (14)$$

and

$$|U| = |Z|^{-1} * |X|^T * |Y| = |Z|^{-1} * |A| \qquad (15)$$

The computed vector $|U|$ gives the procedure finding the TUH ordinates directly from a gross rainfall step by step to reach a net rainfall up to a direct runoff $|YC|$ (Y computed) using standard matrix routines:

$$|YC| = |X| * |U| \qquad (16)$$

Hidden in the manipulation of the matrix algebra on the right side of Eq. (16) is the least-squares curve fitting technique mentioned above but to repeat it to requested close coincidence with a net rainfall and T-Unit Hydrograph ordinates. The improved rainfall data is now used to find a better estimate of the TUH and the whole process is repeated. We were testing the Matrix Inversion Model on a dangerous event in the Jilovsky River catchment. The flooding occurred on 4–5 of July in 2009 (24 h) when a gross rain was falling for about 10 hours. The difference in gross and net rainfall was extremely large: 80 – 10.25 = 69.75 (mm). Table 3 provides the basic parameters of the Jilovsky catchment.

Table 3. Jilovsky catchment parameters.

Catchment area, km^2	45.6	**Land use**	
Elevation, m a.s.l.	730-249	**Forest, %**	52.8
Length of river, km	11.1	**Grassland, %**	37.0
River slope, %	10.3	**Urban areas, %**	9.4

Slope of catchment, %	14.2	**Water areas, %**	0.8

RESULTS AND DISCUSSION

The Unit Hydrograph (UH) was first proposed by Sherman (1932), originally named unit-graph. The UH is a very simple and effective method of the rainfall-runoff simulation, however it cannot be used if there is a lack of data. In this case the synthetic unit hydrograph modifications should be used (Clark’s, Snyder’s, SCS). Since the majority of small watersheds have no recorded runoff or rainfall data, it must be a synthetic hydrograph. Snyder (1938) presented a method of deriving synthetic unit graphs empirically. The study and analysis of rainfall-runoff characteristics were done in ungauged and gauged catchments of the Appalachian Mountains of the Eastern United States. There are two main parameters for the Snyder synthetic UH: the lag factor (Ct) and the peak flow factor (C p). These parameters are topographically dependent and should be estimated for each particular case. In this study both those parameters were derived from measured data (Melching & Marquardt 1997; Ramírez 2000). Snyder’s method was chosen for this study also because it is a part of HEC-HMS software. Many researches have studied the implementation of the Snyder hydrograph, since it is one of the most popular solutions for the ungauged catchments. In their research Hoffmeister and Weisman (1977) used the synthetic unit hydrograph for an ungauged basin in New Zealand. The authors simulated the runoff using three different methods: Snyder’s method, SCS dimensionless hydrograph and Commons’ dimensionless method in six basins of two hydrological regions. The synthetic UH were compared with unit hydrographs based on observed data. The results of research show that Snyder’s method is reasonably accurate. In Europe a good representative study of synthetic unit hydrographs was conducted in Poland, in the Grabinka catchment by Wałęga et al. (2011). The research results show that both Clark’s and Snyder’s methods are applicable, with slightly better results of Snyder’s method. The publication also contains an interesting approach to the estimation of necessary parameters for simulation. The previous study on a comparison of SCS synthetic unit hydrograph and KINFIL model showed that KINFIL model provided better results due to the more natural form of hydrograph. The comparison of simulated runoff by KINFIL model and Snyder’s method shows that the Snyder synthetic hydrograph improved results compared to a previous study on the SCS synthetic unit hydrograph. Figure 5 demonstrates the results of simulation for plots 4 and 5 of the Třebsín ERA. The simulation by both models was made on rainfall with recurrence interval N = 10, 20, 50, 100 years, time duration t_d = 10′, 20′, 30′, and 60′.

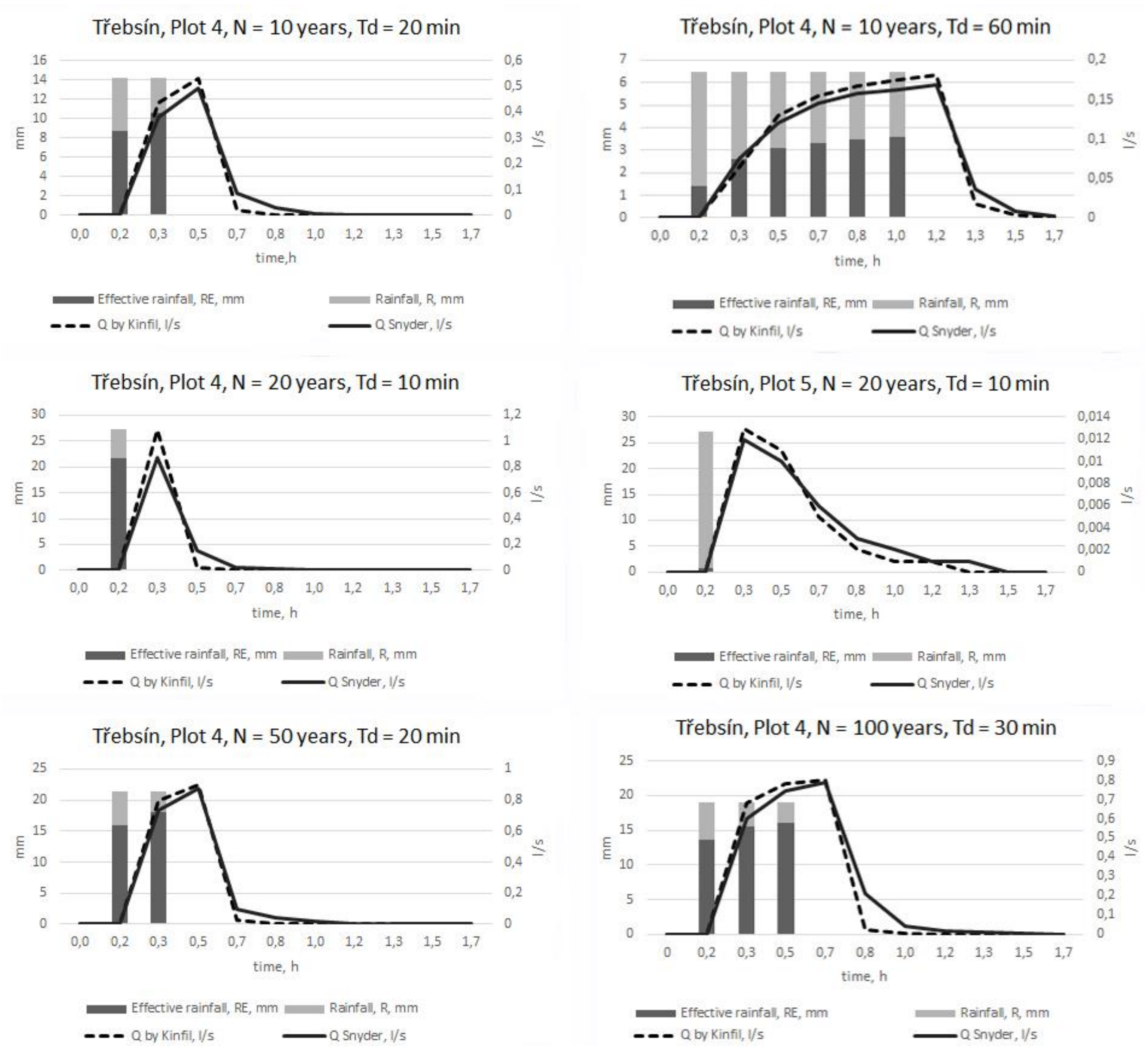

Figure 5. The comparison of hydrographs simulated by KINFIL model and Snyder synthetic unit hydrograph, Třebsín Experimental Runoff Area; N − recurrence interval; t_d − time duration

The Matrix Inversion method was well described by Dooge and O’Kane (2003) and by Mays (2010). If the unit hydrograph is described, it can be used to determine a direct runoff for any storm event by the Matrix Inversion method. Because of the simplicity and accuracy of this method it is quite popular in different variations and climatic conditions among hydrology engineers. The study on the Johor River in Malaysia was done by Razi et al. (2010). The synthetic flood hydrographs were calculated using the SCS Unit Hydrograph method and the convolution matrix procedure. The results of the Matrix Inversion Model for the Jilovsky catchment are presented in Table 4. The calculated hydrograph is presented in Figure 6.

Table 4. The matrix hydrograph reconstruction.

Time, hours	**Gross rainfall, mm/h**	**Net rainfall, mm/h**	**Observed runoff, m^3/s**	**Computed runoff, m^3/s**	**Unitgraph**
0	0.5	0	0.35	0	0.104
1	2	0.01	0.36	0.01	0.267
2	3.5	0.05	0.33	0.04	0.316
3	5	0.15	0.35	0.06	0.332
4	9	0.49	0.37	0.39	0.141
5	25	2.73	0.4	2.78	0.090
6	21	3.7	0.45	1.66	0.007
7	7	1.5	1.23	2.75	0.093
8	5	1.14	24.97	23.82	0.026
9	2	0.48	22.98	23.83	0.055
10	0	0	19.79	19.16	0.006
11	0	0	13.56	14.03	0.022
12	0	0	9.25	8.9	0.013
13	0	0	7.37	7.63	0.018
14	0	0	5.53	5.34	0.007
15	0	0	4.21	4.35	0.010
16	0	0	2.66	2.56	0.008
17	0	0	2.34	2.42	0.007
18	0	0	1.98	1.92	0.005
19	0	0	1.64	1.68	0.006
20	0	0	1.44	1.41	0.003
21	0	0	1.25	1.27	0.006
22	0	0	1.12	1.1	0
23	0	0	0.98	0.99	0.009
24	0	0	0.85	0.84	0
25	0	0	0.73	0.74	0
26	0	0	0.65	0.65	0
27	0	0	0.59	0.57	0
28	0	0	0.52	0.5	0
29	0	0	0.46	0.5	0
30	0	0	0.4	0.52	0
31	0	0	0.35	0.2	0
32	0	0	0.31	0.13	0
33	0	0	0.27	0.05	0

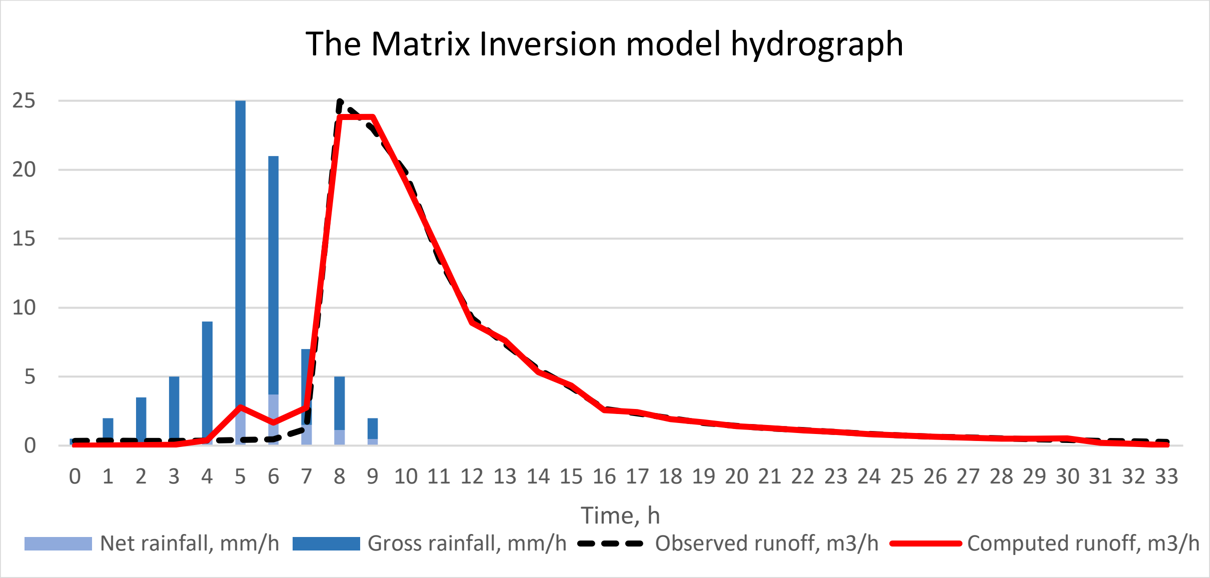

Figure 6. The hydrograph computed by Matrix Inversion method

The successfulness of calibration and validation of models is usually described by the Nash and Sutcliffe Coefficient of Efficiency (CE). In the case of the maximum coincidence CE = 1.00. The equation for the Nash and Sutcliffe coefficient calculation is:

$$CE = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_c)^2}{\sum_{i=1}^{n}(Q_i - \bar{Q})^2} \qquad (17)$$

Where Q_i is observed runoff, Q_c is computed runoff, $\bar{Q}$ is a mean value of observed runoff and *n* is a number of runoff ordinates. Coefficient of efficiency for current study is **CE = 0.989** which is considered to be very high. The efficiency of the Jilovsky catchment is surprisingly accurate.

CONCLUSION

Among all available models for runoff simulation in ungauged catchments different variations of the synthetic unit hydrograph take the leading place, however, it was necessary to consider that there are many effective, physically based models. The previous study showed that the main disadvantage of the applied SCS synthetic unit hydrograph method was its less natural shape. Snyder’s method of the synthetic hydrograph is obviously free of this disadvantage. Nonetheless, the main difficulty is the derivation of necessary coefficients. If this problem can be solved in any manner, this method is considered to be effective for runoff simulation in ungauged catchments, yet, it needs further research on catchments under different conditions. Hydrology as a science expands quickly and a new developed technology shows the priority of physically based methods in gauged catchments. New methodology, such as various time series (Fourier series, Laguerre function, etc.) and inversion via matrices, is developed rapidly in terms of mathematical modelling.

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8. Methodology of dissertation

This dissertation work analyses quantitatively to what extend the land use changes could influence a rainfall-runoff process. It is focused on short-term rainfall-runoff events with a short time step (less than 1 hour). These events are dangerous on small catchments as they cause local floods, or in combination with regional rainfall floods over larger areas. For simulation of these phenomena the KINFIL model and the different components of HEC-HMS software are applied. These models are based on the infiltration process and direct runoff transformation. Land use are simulated by conceptual parameters of saturated hydraulic conductivity, storage suction factor and vegetation roughness through Manning. Data on flood events on the some experimental catchments is examined by KINFIL model with GIS support.

9. Contributions of the thesis

Nowadays, the protection of soil and water resources is especially important topic, because the rates of land degradation and water resources reduction are very high due to the human activities and climate change. One of the possible benefits of this research is to provide the latest knowledge on methods of hydrological extremes control using technical and biotechnical measures, and to gain knowledge on preventive activities.

The current study paid attention to two locations with historical terraces systems, both are in Czech Republic. First experimental area is situated close to the Kninice village, several publications were done in the frames of the study on this area (Kovar et al. 2016, Fedorova 2017) . The terraces system in this location is very well defined. Generaly, terraces have been one of the agriculture techniques since ancient times, the terraces systems can be seen in many parts of the world: around the Europe, in China, in South America, etc. In Kninice the terraces system is formed by the stone hedgerows. The same hedgerows systems can be found in United Kingdom, some of them served as a borders to so-called “Celtic” fields. It is sometimes even suggested that some hedgerows were built in Neolitic era, however it is highly doubtful (Wright 2016). Different studies on the historical structures are made, however most authors focuse on the historical meaning of hedgerows, not on the hydrological characteristics. The study on the Kninice area was made to prove or disapprove the effectiveness of hedgerows formed terraces as an erosion control measure. Previously it was suggested that historical hedgerows impact on overland flow mostly as a physical obstacle, but the precise research showed that actually the effectiveness of those hedgerows in a reduction of overland flow is due to the higher infiltration as a cause of the used material. However, it is necessary to mention, this erosion control measure works effectively for historical fields without extensive agriculture – the experimental area consists mostly of meadows. For the fields with active crop growth the additional measures should be used, as the study on the Smeda catchment concludes (Kovar 2017). Those advisory results could be used by agriculture services for the erosion control and effective planning of agriculture techniques and activities, with an additional study it is possible to estimate the cost of supplementary erosion control measures.

The other outcome of studies on Kninice and Smeda catchment is the application of hydrological models to estimate the surface runoff. For any natural resources, such as soil, water, etc management it is very important to have adequate information. In the case of soil erosion this necessary information is data on overland flow. Of course, it is highly sensitive to the chosen method of estimation. The current study describes the advantages and weaknesses of applied models. The results simulated by KINFIL model were compared with the results estimated by SCS dimensionless Unit Hydrograph (Fedorova 2017) and Snyder's Synthetic Unit Hydrograph (Fedorova 2018) models.

The main focus in this work was made on the small catchments because of the importance to the soil erosion process and slightly easier measurement and estimation of parameters. It is often adviced to divide the middle-sized and big catchments on the smaller subcatchments for implementation of soil erosion simulation models. But the main difficulty was that the all experimental catchments were ungauged, so there is no rainfall-runoff data available. The majority of small catchments, which are soil erosion sensitive, are ungauged. No need to say, the methods and approach for the surface runoff estimation would be attractive for any state organization interested in soil management.

In general, the current work could be used in the design or as advisory study on prevention of hydrological extremes, the formed knowledge from the thesis also could be used in project implementation solutions for landscape planning or as a good basis for further studies. The gained experience, with some adaptation, could be used by the engineers-hydrologists in other countries; the results could be applied in state hydro-meteorological, agriculture, river basin control services.

10. Conclusion

The main purpose of this thesis is the assessment of factors influencing the hydrological extremes and soil erosion and advises on control measures. The research is done on the several experimental areas, using different techniques of estimating the harm on the soil resources of natural factors, such as meteorological conditions, the impact of geomorphological factors, etc. and the impact of land use. The choice of the software for the current study is based on the accessibility and the usefulness in combination with accuracy. The various factors influencing the floods and soil erosion formation are studied; the details of different components of hydrological processes are investigated. The effectiveness of existing biotechnical measures is evaluated too; the possible ways of development are given as advisory measures.

The current study is based on theoretical assumptions, empirical data of experiments and on the experience and various studies in thematically related fields all around the world. The results of this work can help the water resources and agriculture engineers to make necessary decisions in the field of control and protection of water and soil resources.

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- Fedorova D., Bačinová H., Kovář P.(2017): Use of terraces to reduce overland flow and soil erosion, comparison of the HEC-HMS model and the KINFIL model application. Soil & Water Res., 12, 2017 (4), 195–201. DOI: 10.17221/160/2016- SWR
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- Fedorova D., Kovář P., Gregar J., Jelínková A, Novotná J. (2018): The use of Snyder synthetic hydrograph for simulation of overland flow in small ungauged and gauged catchments. Soil & Water Res., 13, 2018 (1): 00–00, DOI: 10.17221/237/2017-SWR

Accepted by Journal:

- Andrea Jelínková, Darya Fedorova (2018): Effect of external conditions on water quality in the Kamencove (Alum) lake in Chomutov. Scientia Agriculturae Bohemica, 2018 (accepted manuscript on July the 11th 2018, under revision)

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