Chapter 10
Modelling of the Water Retention Capacity of the Landscape

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10.1 Introduction

The number of extreme hydrological events has rapidly increased in the last hundred years. The accrual of floods has been a consequence of increased runoff from the landscape and this runoff has been caused by a decrease in flood storage capabilities. The areas with low flood control capability have increased with more and more frequency in the watersheds because the diversity of the landscape has descended and the whole landscape structure has been weakened.

It is necessary for a project of structured changes in a watershed to rate the proportional representation of various land use forms, their spatial distribution, their shapes and the orientation of their segments. These projected landscape modifications should lead to an increase in flood storage capability. Optimally structured remedies with a precise localization should then be made after an extensive and thorough analysis.

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10.1.1 *Influence of Landscape Segments on River Basin Retention Capacity*

The condition of maintaining a balanced state of water in the landscape is its continuous circulation. A suitable unit for studying the hydrological cycle in the landscape is a small river basin [1], because it is drained from the surface and underground drainage water and its topographical distribution is identifiable. A small river basin is a river basin with a surface where the nature of the river basin, in particular, its geophysical properties and management, is fully utilized for the formation of runoff, and its influence is not suppressed by the characteristics of the flow capacity of the riverbed [2]. The term 'retention capacity of the landscape' is based on the definition [3], which means temporary retention of water on vegetation and objects in the basin, retention of water in the cover layer of soil, in soil, micro-depressions, polders and tanks in the so-called phase of the precipitation–runoff process. The retention capacity of the landscape depends on the depth of soil profile, soil grain composition, skeletal content, humus content, structural state and porosity and the type of landscape cover and its condition.

Forest areas fulfil a significant water management function. According to the forests division in the Czech Republic [4], the category of forests, which are of water management significance, account for 27.6% of the total forest area in the Czech Republic. These are declared protected areas of natural accumulation of surface water—CHOPAV (16%) and forests in the sanitation protection zones—PHO (9.6%) [4].

The water management functions of forests consist mainly in ensuring the permanence and yield of water resources, in decreasing flow fluctuations (retardation and retention, accumulation of runoff) and improving the quality of runoff [5, 6]. Decree No. 83/1996 Coll. defines the partial water management functions of the forest:

- water protection (ensures water quality and protection against erosion)
- anti-erosion (prevents surface runoff)
- infiltration (conditional to maximum infiltration of rainwater into the soil)
- detention (dampens extreme drains from small river basins)
- suction (drains excess water from the soil)
- precipitation-inducing (capture horizontal precipitations).

In particular, the vegetation component and the hydrophysical properties of the soil contribute to the fulfilment of the water management function of the forest.

The vegetation cover is used for the retention and change of surface runoff velocity, mainly by evaporation of water back into the atmosphere and evapotranspiration of crowns [6]. What is important is that the forest evaporates the water that the roots of trees intake from relatively deep soil horizons. The high infiltration capacity of forest soils is due to very good aeration thanks to the interconnection of the root system with soil organisms and soil. The pores occupy about half of the soil volume on average. Moreover, a high layer of humus horizons under the quality forest stands almost excludes the possibility of surface runoff [6]. The vegetation component, and land as well, can be influenced by economic measures, e.g. by choosing species composition, changing the representation of age classes, changing the density of crops, forest renewal, timber harvesting and concentrating technology, preparation of planting area and forestry mitigation measures [4]. Their influence on the hydrological functions of the river basin has been described in a number of works [4, 7].

Species composition of the forest. Restoration of the beech stand from 80% by Norway spruce has not contributed to the increase of flood waves. Only in the downstream part of the flow wave are drains from the restored river basin higher [7, 8]. When compared to spruce and beech stands, more favourable quantitative water balance was found in beech stands (in spite of the lower sum of interception and evapotranspiration in beech stands was lower by 30–145 mm/year) [6]. The intercept values varied, with the greater ability of spruce to intercept precipitation. Significantly, lower leakage into the subsoil was characterized by spruce stands [6]. In general, broad-leaved stands tend to exhibit higher infiltration values than coniferous stands.

Deforestation. Wood harvesting and changes in land use have resulted in increased peak flow rates [6]. This applies to permanent deforestation (pastures, roads, etc.). However, the forest soil after the extraction of old or calamitous stands, which are subsequently restored by planting, does not lose its retention and retardation abilities according to [6]; common cultivation and restoration measures can affect the genesis of flow waves to the extent that is barely measurable and conclusive [7]. Any reduction in evapotranspiration is very quickly replaced by the functions of a compact herbaceous layer [8].

Drainage. After dewatering, the depression curve and the minimum groundwater level (lower aeration of the soil profile in the root part and its release for rainfall) have changed; there was no deterioration in water conditions in dry soil [4]. For their hydrological significance, floodplain forests deserve a special chapter, thanks to their considerable retention capacity, adaptation to high groundwater levels and floods. However, since floodplain forests do not occur in the area under review, this issue is not discussed further.

Grasslands. Grasslands appear to be very perspective cultures, as they have many ecologically significant features from the hydrological point of view. The associated tussock stand has on average 10% greater porosity than the arable soil [9], which is a more favourable soil structure, which allows better flow and drainage of flood and rainwater [10] in their work point to significant differences in the infiltration capacity of different lawn grass species. In relation to hydrological conditions, the content of organic matter in soils under permanent grasslands is also important, which is reflected in their retention capacity [11, 12].

The biologically active surface of the plant matter is also important for the hydrological effect in the landscape. This year, this surface forms an intermediate between the soil and the air and its size varies from 1 to 10 m^2 of leaf surface per 1 m^2 of vegetation. The biologically active surface has significance in interception and evapotranspiration. [9] states that meso- to hygrophytic meadows have a very intense water operation, which has a transpiration effect that exceeds the evaporation from the water level. The use of grassland also has a significant impact. Lawn grassland usually uses water more rationally than on grassland. The reason for this is that the grassland is more frequent during excessive water consumption or loss of water [13]. It also forms an insulating layer that reduces direct evaporation from the soil and thus maintains greater soil moisture in the soil. Elimination of the turf pool results in volatile hydrological conditions. The transformation of grass biomass through animal production into animal fertilizers is also of great significance, which helps to improve the fertility and hydro-pedological properties of arable soils [12].

Arable land. Also, arable land is a significant hydrological factor contributing to the formation of the landscape water regime. Unlike other categories, agricultural land is characterized by intense seasonal dynamics of porosity, permeability, micro-relief structure or species structure, and thus in the quality of the vegetation cover.

Volume density, porosity and soil infiltration are closely related to the type of crops grown. Relatively high infiltration capability is characterized by the soil of the grain sites and the habitat of the manually treated meadows. The smallest infiltration capacities have mechanized-field meadows, soils with corn and Lucerne crops and land without vegetation, especially with the hardened surface after heavy rains [14]. In [14], relationship between causal rainfall and surface drainage on differently exploited experimental areas of agricultural land (bare soil, grassland, alfalfa, winter wheat and stubble) is treated. At regional rainfall, the values of surface runoff coefficients at all sites of individual crops were very low (<0.1000). Moreover, the occurrence of such long-lasting rains usually falls into the summer season, when the soil is already sufficiently protected by vegetation. Multi-year forage crops, winter wheat or berries do not, therefore, contribute significantly to floods. On the other hand, local rainfall (spring and early summer) caused mainly on bare soil, freshly agro-technically processed, many times larger surface drains and as such contribute to local floods [14]. Also, micrography produced by agro-technical soil treatment is characterized by some surface and internal retention ability.

Intensification of agricultural production often leads to a negative influence on the infiltration capacity of the soil (soil compaction, the addition of root crops at the expense of perennial forage and grassland). Depending on these changes, hydrological, especially rainfall-flow processes in the landscape change [14]. On the other hand, it is possible to use more sophisticated technologies of soil processing (soil preparation and sowing in one operation, sowing in a winter crop mulch, etc.) that do not deteriorate the water balance of the habitat (do not harden soil, soil cover reduces unproductive evaporation, etc.) [13].

Scattered greenery, linear communities. Significant hydrological functions in the landscape ecosystem can be fulfilled by elements such as scattered greenery, linear communities or other linear elements (shingles, singularity woods, boundaries, high limits, tapes, windbreaks, hedges, streams, trenches, avenue tree plantations, etc.). In the landscape, the surface flow is affected by the corresponding cause.

In varying degrees and configurations, line elements are scattered across the landscape: in lines; networks and clusters. Particularly in agricultural-managed river basins, they are important and often the only stabilizing elements. Even a multimeter sinking strip, separating arable land, positively changes the conditions of the vat, thereby increasing the proportion of sub-surface runoff. Sajikumar and Remy

[15] states that the soil under mixed woody and grass vegetation of most of the eco-stabilization formations shows mentioned above is absolutely exceptional and hydrologically relevant, and has decisive volumes of influential soil infiltration capacity.

10.1.2 Geo-Information Technology

Geo-information technology (GIT) encompasses the modern processing of spatial data using information technology. The rapidly evolving information society sees GIT becoming an integral part of many fields of human activity, among them science subjects which study the spatial distribution of various phenomena, their characteristics and relationships. GIT has applications primarily in geographic information systems, remote sensing, global positioning systems and computer cartography [16–18].

The geographic information system (GIS) encompasses complex information systems that integrate tools from a number of science fields and are characterized by their ability to process spatial data actively and efficiently. One of the widely used definitions states that a geographic information system is a system designed to capture, store, transform and visualize spatial data representing the real world with respect to a specific application [19]. Also, a geographic information system allows the collection, processing, and management of geographic data related to natural resources, provides a more accurate representation of reality in a computer environment, decision-making processes easier [20, 21]. It also allows its users to model a number of natural processes, consequently, facilitating the planning of utilization and predictions of natural resource management development [22]. The term 'GIS' may be applied only to a system containing tools that fully cover the four key areas of functionality. Such a system allows the creation, utilization and updating of extensive databases of thematically diverse spatial data [23–25].

The broad application of GIS in environmental database management is driven by a comparison of GIS potential with other technologies. GIS is suitable for data management for the following reasons [26–28]:

- they are readily applicable to several different tasks,
- use identical data for different studies and save such data,
- is capable of fast processing of large data volumes,
- is capable of processing data in varying levels of detail (in different scales),
- allow easy conversions of raster and vector structures, making them flexible in data application in different data structures,
- help to standardize data from different sources.

The Czech Republic has a sufficient amount of data sources representing the landscape and its features. However, their availability, up-to-date and a very diverse structure (with respect to both content and format) pose a problem. 'The accuracy and detail of input data influence the quality of consequent analyses and outputs'

[29]. Overview of individual data sets available in the Czech Republic and suitable for landscape analyses are presented by [26, 30] or [31].

10.2 LOREP

The formulated LOREP model represents an application of the solution using a methodological approach for the identification and localization of areas with low flood storage capability. This makes it possible to compare the projected scenarios. The structured catalogue of non-technical solutions for the landscape is a part of the model.

The modelling approach is based on a study of storm runoff computing using spatially distributed terrain parameters published by the Center for Research in Water Resources at the University of Texas [1]. The main part of the water flowing from the basin is a widespread feature of the hydrograph unit. The study describes in detail how it is possible to refine the final value of the surface runoff. The terrain model is a loaded grid dividing the basins studied in the same parts, and each character is related specifically to the sub-areas mostly square. This division into several smaller parts is the result calculated with the inhomogeneity of the area, which was used in the calculations for the basin as a whole is mostly wiped away. It is a distributed hydrological model with a partial semi-empirical approach [1].

The fact that linear features (such as lines of trees) can be a part of land use analysis is the key element of the model. This is possible because the raster data of high resolution (pixel size 5 m) is used and because the modelling is focused on the hydrology of small basins [1]. The procedure for the computation of territorial-specific surface runoff is based on a combination of specific functions in GIS, hydrological equations of the runoff curve number method and spatially distributed unit hydrographs. The LOREP model is written in Python and is designed for ArcGIS. The input data are expressed as a grid of pixels in agreement with the rules of raster representation in ArcGIS. The spatial resolution of the pixels is selected so that it is high enough to identify the influence of linear features on the landscape on the extent of surface runoff [32].

10.2.1 Calculation of Specific Surface Runoff in the Territory

The computation of the area's specific surface runoff is a determinant step for the localization of areas with low flood storage capacity. These raster data of high resolution are input layers for the analysis of surface runoff in the model:

- hydrologically correct Digital Elevation Model [33],
- a raster of curve number method (CN-values),
- a raster of land use.

It is possible to use any method of producing digital elevation model (DEM), but it is necessary to adhere to the rules of creating a correct DEM (e.g. uniform format and resolution). Raster of CN-values is created according to the methodology recommended for the Czech Republic [34]. If the area does not contain forests, the CN-value is determined by combining data and land use categories plotted in the soil type map and in the complex survey of soils. If the area contains forests, hydrologic groups of soils are derived from the forest typology unit [35]. The process assumes and zero previous rainfall. The layer of land use is created/updated with the help of data sets ZABAGED (Fundamental Base of Geographic Data) and orthophoto map of the relevant basin. The field survey has to be realized in poorly identifiable areas. The values of Manning's roughness coefficient are determined by the land use categories according to the conversion tables [34].

10.2.1.1 Creating a Hydrologically Correct Digital Relief Model

The Digital terrain model (DMT) is a raster expression of the altitude gradient. Hydrologically correct DMT [36] means that it allows hydrological modelling. Some variants of DMT calculations do not take into account phenomena such as local depression or local elevations. On the contrary, they create 'fictitious' depression due to erroneous interpolation. The model thus created does not allow (or rather allow, but with errors) hydrological modelling, i.e. mainly direction and drainage calculation, drained area and so on.

Calculation of hydrologically correct DMT is based on a special variant of the spline interpolation method that, among other things, optimizes the calculation and permits rapid changes in terrain relief and applies algorithms to calculate dewatering. The model thus calculated has eliminated unreal pits and peaks.

10.2.1.2 Iteration Cascade

The principle of the cascade is the gradual calculation of the height of the direct runoff for each pixel in the basin according to the basic equation of the CN-curve method (formula 10.1), that is extended here about the influence of the terrain on the direction and length of the surface runoff. To apply a model, pixels throughout the river basin need to be 'categorized' into iterative orders. This is done by the combination of the derived drainage direction and the run length using the flow length command.

First, all local topographic maxima in the basin are determined. These are pixels whose altitude is close to 3 × 3 pixels highest, and identify vertices or divides—i.e. places where the drain begins, and there is no accumulation. From these points, the surface runoff path (direction and length) is determined. The distance from the topographical maximum divided by the width of the pixel then determines the order of the pixel (Fig. 10.1).

The division of the catchment into the iterative order ensures that the impact of the terrain is reflected in the calculation of the surface runoff and allows to track the direction and length of the runoff from the point of origin to the catchment point of the river basin. This greatly helps to better identify critical sites in the landscape [3]. The input layers in the iteration cascade are the possible retention raster, the pixel raster order and the design precipitation raster.

The draft precipitation represents the 24-h total precipitation H_S (in mm) in the area. To compare the retention capacity of different parts of the river basin, its value is constant for the entire catchment area. In this study, precipitation with a volume of 4 mm was used as mild rain and precipitation of 20 mm as torrential rain.

The iterative cascade routine is composed of N iterations, where $N =$ number of pixel orders. In each iteration, the height of the direct flow H_{O_X} for Xth order pixels is calculated according to the equation:

$$H_{O\_X} = \frac{\left((H_{S\_X} + H_{P\_X}) - 0.2 * A\right)^2}{(H_{S\_X} + H_{P\_X}) + 0.8 * A} \text{ (mm)} \tag{10.1}$$

where

A	the potential retention of 1 pixel unit in mm
H_{O_X}	the height of the direct outflow from the Xth order pixel area unit in mm
H_{S_X}	the height of the rainfall on the Xth unit pixel area unit in mm
H_{P_X}	the height of direct water inflow in mm from pixels of the order $X - 1$ depending on the direction of drain.

The direct inflow height value in the Xth order pixel H_{P_X} is calculated by summing the H_{O_X-1} pixels by one order of lower ($X - 1$) that flows into the given pixel based on the slope direction. Since zero water cannot flow from the higher positions to the 0th order pixels, their $H_{P\_X} = 0$. The output of the 'iterative cascade' is the raster of

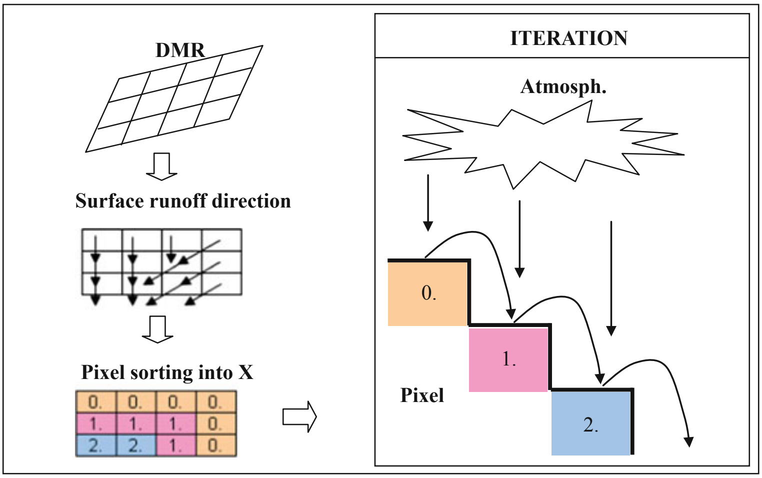

Fig. 10.1 River basin division into iterative order

the cumulative H_{OK} flow height in mm, which is given by the H_O raster sum of all iterations.

10.2.1.3 Drawing Direction

The calculation of surface flow into multiple directions is based on a solution based on the [37] topographical index, which is now successfully implemented in several hydrological models, e.g. in TOPMODEL [38].

The algorithm is based on the fact that the received part of the surface runoff from the monitored pixel, in each pixel downhill, is given by the percentage of the weighted impact distance of the precipitation and the geometric weight factor that depends on the direction of the drain.

$$A_i = A \frac{tg\beta_i * L_i}{\sum_{j=1}^{k} tg\beta_j * L_j} \tag{10.2}$$

where

A_i the share of the source region to neighbour i (m^2)
A upstream slope area possible for flood subsidy (source area) (m^2)
β_i slope gradient (= slope difference) towards neighbour i
L_i weight factor (0.5 for direct and 0.354 for diagonal direction)
k number of lower neighbours.

The basic benefit of this algorithm is that it divides the flow between several recipients. Most models use the D8 method [17]. Eight nearest neighbours for the given pixel is found, and the difference between the altitude values between individual pixel centres and the distance of individual centres (3 × 3 filter) is calculated based on the input DMT. Because the calculation is done in a regular grid, the distance is constant.

The direction of the drain is given by the steepest slope, and all the volume flows in only one direction. However, it is not so in nature, and it is much more advantageous to use the algorithm to calculate the surface runoff in multiple directions for a greater approximation to reality.

10.2.1.4 SCS Curve Number Method

The runoff curve number (also called a curve number or simply CN) is an empirical parameter used in hydrology to predict direct runoff or infiltration from rainfall excess. The curve number method was developed by the USDA Natural Resources Conservation Service [1, 39], formerly called the Soil Conservation Service or SCS. The runoff curve number is based on the hydrological soil group, land use, treatment and hydrological condition. References, such as from USDA, indicate the runoff curve numbers for characteristic land cover descriptions and a hydrological soil group. The basic assumption of the SCS curve number method is that, for a single storm, the ratio of actual soil retention to runoff is equal to the ratio of direct runoff to available rainfall [1, 39]. However, the results of its application in larger river basins are well known [39].

The purpose of the method is to quantify the hydrological functions of landscape components. The method takes into account the dependence of the retention of the basins on the hydrological properties of soils, the initial state of soil saturation and the way of land use and hydrological conditions.

Outflow is primarily determined by the amount of precipitation, the infiltration of water into the soil, soil moisture, vegetation, impervious surfaces and surface retention. The basic input of the CN-curve method is the rainfall sum of a certain time division, assuming its uniform distribution over the river basin area. The amount of precipitation is converted to the volume of runoff by the number of drain curves. Their values depend on the hydrological properties of soils, the vegetation cover, the size of impermeable surfaces, interceptions and surface accumulation.

Drain curve numbers are tabulated according to the hydrological properties of soils divided into four groups: A, B, C and D on the basis of minimum water infiltration rates without covering after long-term saturation and utilization of soil, vegetation cover, cultivation and application of anti-erosion measures.

The method thus proceeds from the assumption that the ratio of runoff volume to total rainfall is equal to the ratio of the volume of water retained at runoff to the potential volume that can be retained. Drainage usually begins after a specific accumulation of rainfall, i.e. after a certain initial loss, which is the sum of interception, infiltration and surface accumulation estimated on experimental measurements at 20% potential retention ($I_a = 0.2$ A).

From the above-mentioned context, the basic relationship was derived:

$$H_O = \frac{(H_S - 0.2\ A)^2}{(H_S + 0.8)}\ (\text{mm}) \quad \text{for } H_s \geq 0.2\ \text{A} \tag{10.3}$$

where

H_o direct drain (mm)
H_s the sum of the draft (precipitation) (mm)
A potential retention expressed by CN curves.

as

$$A = \left(\frac{1000}{\text{CN}} - 10\right) \times 25.4 \tag{10.4}$$

Of which volume of direct drain O_{pH}:

$$O_{pH} = 1000\,.\,P_p\,.\,H_0\ (\text{m}^3) \tag{10.5}$$

where

P_p the area of the river basin (km^2),
H_o direct drainage (mm).

The basic step of the whole process is to create a raster that carries the CN-curve value. This layer is obtained by combining the following three factors that were captured in the raster form.

Land use. Combining the digital layers of the ZABAGED geographic database and evaluated colour orthophotograph images, land use grid was created. The spatial resolution of the raster was chosen at 5 m, taking into account the fact that the model was able to capture the influence of the linear elements of the landscape (road network, boundaries, reminders, etc.) on the formation of direct outflow volume in the landscape. The pixel resolution of 5 m, in reality, corresponds to 25 m^2 landscape. This section of the landscape is considered homogeneous. In case of occurrence of 2 categories in a given pixel, the value of a category with a larger share is taken after the pixel value. The raster has been verified and updated by field research. Categories of land use have been unified with the CN-curve categories.

Based on raster representation rules, line and planar entities are rendered as squares. In this detailed scale, line elements such as boundaries or paths form a series of pixels. The influence of their orientation on the direction of the surface runoff is captured at the time of the combination of the land use grid with the digital landscape model. A line that is represented by an entity of a given width, such as one pixel, influences the drain only in this narrow band. In contrast, a line that is at a sharp angle or perpendicular to the flow direction is represented by multiple pixels in width, and its effect is reflected on a larger surface (relative to the direction of the surface runoff).

The hydrological properties of soils were derived from the BPEJ (valuated soil-ecological unit) codes for agricultural and urbanized areas on the basis of existing transfer tables [34, 40] and for forest soils based on selected soil characteristics. The existing division into four groups was further specified on the basis of field measurements and expert estimates of up to eight sub-categories. On the basis of the measurements, the boundary between individual sub-categories in the field was also specified [41].

The transitions between the hydrological properties of the soils are in nature rather gradual, not sharp. Therefore, this layer falls into its non-shady set. Nevertheless, the pedological survey in the Všeminka basin has demonstrated an almost sharp boundary between individual hydrological types and their properties, mainly due to the geological and geomorphological characteristics of the area (Bayer, oral statement). For this reason, the hydrological properties of the model were presented as a sharp set of rays.

The moisture content of the soil before the precipitation is calculated based on the five-day sum of the previous precipitation (see [34]). This magnitude can also be ranked by fuzzy sets based on spatially variable precipitation totals. For simplicity, however, a raster containing the value of Antecedent Precipitation Index (API II) scalar variable was used.

10.2.1.5 Unit Hydrograph

A hydrograph is used to more easily represent the effect of rainfall in a particular basin. It is a hypothetical unit response of the watershed to a unit input of rainfall. This allows easy calculation of the response to any arbitrary input (rainfall) by simply performing a convolution between the rain input and the hydrograph output unit [1]. An instantaneous unit hydrograph is a further refinement of the concept. For an IUH, the input rainfall is assumed to all take place at a discrete point in time (this is not the case for actual rainstorms) [39]. Making this assumption can greatly simplify the analysis involved in the construction of a hydrograph unit, and it is necessary for the creation of a geomorphological instantaneous unit hydrograph (GIUH). The creation of a GIUH cannot be given more than topological data for a particular drainage basin. In fact, only the number of streams of a given order, the average length of streams of a given order and the average 'land area draining directly to streams of a given order are absolutely required (and can be estimated rather than explicitly calculated, if necessary)' [1].

10.2.1.6 Direct Runoff

The procedure core point is an algorithm of the direct runoff capacity $Q(t)$ with spatially distributed terrain parameters [42]. This algorithm (see formula 10.6) makes it possible to trace the direction of the surface runoff in the landscape and to specify the influence of the terrain on the runoff.

$$Q(t) = \sum_{i=1}^{Nw} \int_{0}^{\infty} A_i I_i(\tau) U_i(t - \tau)\mathrm{d}\tau \tag{10.6}$$

where

$Q(t)$ the direct runoff from the concerned basin

t time

N_{i-w} the number of sub-basins

A_i the area of sub-basin i

$I_i(t)$ the excess precipitation in sub-basin i (direct runoff from basin i, see formula 10.7)

$U_i(t)$ the flow-path response function (response at the basin outlet yield by a unit instantaneous input in sub-basin i, see formula 10.8).

It is necessary to divide the basin into uniform non-overlapping sub-areas (sub-basins in grid structure) and for the application of this algorithm and to calculate $I_i(t)$ and $U_i(t)$ for each sub-basin (see formulas 10.7 and 10.8).

$$I_i(t) = \alpha_i \; Pe(t) \tag{10.7}$$

where

$I_i(t)$	the excess precipitation in sub-basin i (based on the appraisal of the balance in the ‘soil–water’ system)
t	time
α_i	the compensative index
$Pe(t)$	the precipitation excess.

$$U_i(t) = \frac{1}{2t\sqrt{\pi(t/T_i)\Delta_i}} \exp\left\{-\frac{[1-(t/T_i)]^2}{4(t/T_i)\Delta_i}\right\} K_i \tag{10.8}$$

where

$U_i(t)$	the flow-path response function
t	time
T_i	the mean distribution value
Δ_i	the scatter around the average of the distribution
K_i	the flow-path loss factor (determines the loss of water along the flow path).

The curve number method is used for the calculation of excess precipitation in sub-basin i. This method takes into account the fact that the flood storage capacity depends on the hydrologic attributes of the soil, on the initial condition of the water saturation in the soil and on the land use activities in the landscape. A detailed description of the algorithm and its derivation is in [42].

10.2.2 Area of Hydrologic Zones in the Basin

The basin is divided into hydrologic zones. It is necessary to know in which zones the areas with high $Q(t)$ are located for the selection and application of appropriate flood control measures. Topography determines ecological conditions such as slope orientation, the gradient of slope and energy supply. This means that the trophic and water relations of the zone and the amount of transported solids from the zone are changing dynamically. Terrain can be differentiated into zones with different attributes as follows:

- Denudation zone—The supply of solids is minimal, and the loss of solids is considerable. The zone’s resistance to extrinsic load is very low (an example of the zone: plateau),
- Transfer-denudation zone—The amount of solids supplied is less than the amount of lost solids. The resistance of the zone to the extrinsic load is low (an example of the zone: convex slope),
- Transfer zone—The amount of supplied solids and the amount of lost solids are equable here. The resistance of the zone to the extrinsic load is moderate (an example of the zone: plain),

Table 10.1 Classification of relief elements into hydrological zones

Relief	Zone
Peak	Denudation zone
Ridge	Denudation zone
Saddle	Accumulative areas
Flat	Accumulative areas
Ravine	Accumulative areas
Drink	Accumulative areas
Convex hillside	Transfer-denudation zone
Saddle hillside	Transfer-denudation zone
Slope hillside	Transfer zone
Concave hillside	Accumulative-transfer zones
Inflection hillside	Accumulative-transfer zones
Unknown hillside	Transfer zone

- Accumulative-transfer area—The amount of solids supplied is greater than the amount of lost solids. The resistance of the zone to the extrinsic load is high (an example of the zone: concavity slope),
- Accumulative zones—The loss of solids is minimal, and the supply of solids is considerable. The resistance of the zone to the extrinsic load is very high (an example of the zone: alluvial plain) (Table 10.1).

The relief classification is based on polynomial surface transformation for the 3 × 3 pixel region. The pixel characteristic is obtained as the second derivative of the fourth degree directional equation for the central pixel of the analysed area. The characteristic value includes information about the rate of change in the tangent ratio to the mathematically described curve in a straight and diagonal direction for orientation of the observed pixel. Since each pixel provides information on the shape in multiple scales, Fourier analysis techniques reduce the variability of the digital model of the territory and improve the calculation result for the solved area [43].

The algorithm of the hydrological zone grid in the basin is a part of LOREP and it is consistent with the work [44], which classified 11 basic landforms and reclassification to five hydrological zones.

10.2.3 Localization of Areas with High Surface Runoff and Detection of Reasons for Low Flood Control Capability

The next step is to create two grids. One grid is connected to the database of information for each pixel in the basin about its geographic conditions. The conditions are soil conditions, vegetation conditions in forests, gradients of land, land use, land cover and hydrological zones. The conditions in the database are deduced from GIS layers containing this information.

The second grid is connected to the database of information for each pixel in the basin about its direct runoff $Q(t)$. There are five categories for $Q(t)$: very high, high, middle, low and very low. It is possible, by using the tools of the map query in GIS, to find the pixels with a very high or high direct runoff and by using the tools of the database query in GIS for these pixels to find their geographic conditions.

We can determine the areas with a very high or high direct runoff thanks to the second grid and the information in its database. We can also detect the reasons for the low flood control of these areas thanks to the grid with the information about the basin conditions. Information about the conditions in the basins and the direct runoff in the basins is gathered from the third step of the procedure. The most important indicator is the amount of pixels in the categories 'high' and 'very high' whose direct runoff in various scenarios must be compared. When we combine the conditions and suggest the measures for each combination in LOREP, we design the scenario for this concrete situation. We simulated various scenarios for each area of low flood control capability found in the third step of the procedure, and we have modelled new layers in GIS with modified land use in the basin. We modelled each scenario with one layer, which always participated in the previous steps. The map of the potential surface runoff, the table with the amount of pixels can be prepared for each scenario. The results are compared, and a recommendation is made for the most appropriate measure for each area of low flood control capability.

10.2.4 Structure of Model

The model for the calculation of the runoff over each pixel has been created according to the above equations, the selected function unit hydrograph. Specifically, the tool can be connected freely through ArcToolbox, which was written in ArcGIS as a script in Python synta10. The resulting toolbox is called LOREP. The tool handles the layer showing the catchment areas in GRID format and shapefile. Its resolution is limited by the digital elevation model (DMR) input resolution. Schematic representation of the calculation of the surface runoff was created by ModelBuilder in the environment. The toolbox is a fully functional data over any river basin in the Czech Republic. This limitation is given only by the Czech name of the land use category in this layer.

The input data are vectors characterizing the area (elevation, water flows and land use) and a layer containing the special characteristics of the basin (the layer with the values of the CN curves and hydrological categories group soils). Other inputs represent the numerical value of the average flow rate, the total catchment area, the rainfall and the time at which the drain is to be found.

ArcGIS Desktop 10.x is a professional tool for creating and managing geo-information systems from Esri. It consists of a set of integrated and mutually cooperating software applications ArcMap and ArcCatalog. Geoprocessing is a fundamental part of working with ArcGIS. It includes all basic and professional operations on spatial data. When creating your own tools in the form of a script created by ModelBuilder, it is possible to use geoprocessing tools [45].

Python 2.5 is a dynamic, object-oriented programming language. This is a hybrid language—allows other programs to share the same letter code. He became popular and widespread due to his simplicity. The code is compared to other languages short and readable. Python code can be written in any text document. For easier use in the OS Windows platform is also available as Python Win [46].

10.3 Case Study—Všeminka

10.3.1 Study Area

Všeminka (21.51 km^2) was selected as an example of small watersheds in the agricultural-forest culture landscape. These watersheds are of IV order and mainly in the location of land use categories in watersheds. The watercourse of the upper part of the River Dřevnice (22.58 km^2) differs from Všeminka watershed in the forest cover (81%) and the type of watershed (Všeminka—valley type of watershed). More detailed testing of methods for retention ability and proposed measures of effectiveness was performed only in Všeminka watershed (Tables 10.2, 10.3 and 10.4).

10.3.2 Results

The CN-values (Fig. 10.2) were determined using the described methodology. Five categories of the actual surface runoff, computed by the 'direct' outflow model for two selected rainfall intensities (Table 10.5), together with spatially generated hydrological zones of catchment (zone of infiltration, transport zone and accumulation zone) entered the main process for identifying the source patches with an extreme runoff.

Table 10.2 Basic characteristics of the catchment areas GIS-derived bases

River basin (km^2)	21.51
Flow length (km)	9.2
The average slope of flow (%)	3.6
The mean slope of river basin (%)	19.4
Minimum altitude (m)	270
Maximum altitude (m)	620
Average height (m)	400
Afforestation of the catchment area (%)	48.2
River basin circumference (km)	23.64
Length of lineages (km)	13.81

The map database queries have been used over the raster layer to determine the possible causes of low retention in these patches (Table 10.6). A new spatial scenario of land use changes per hydrological zone was proposed, based on the findings of most possible low retention reasons and the attitude of precautions. The land use GIS coverage was updated according to this scenario and used again in the 'direct' runoff model per pixel to calculate a potential surface runoff for improved landscape structure under 4 and 20-mm rainfall.

The resulting areas of the simulated outflow categories for the recent land use of Všeminka catchment as well as for the proposed scenario of land use changes are shown in Table 10.5. From Table 10.7, we can conclude that the planned scenario of precautions significantly increased the landscape retention for a temperate rainfall; 66 ha of very high and 207 ha of high surface runoff were reduced to approximately 6 and 20 ha, respectively. Unfortunately, only a tiny reduction of the outflow occurred in the case of the storm rainfall. Stronger precautionary steps or other methods of soil protection leading to the surface runoff reduction shall be used for rainfall of such intensity.

Table 10.3 Land use in the catchment

Usage of territory	Area (ha)	Area (%)
1. Arable land, landfills	201	9.3
2. Meadows, permanent grasslands, lady	521	24.2
3. Public greenery, gardens, orchards, flower beds	117	5.5
4. Built-up areas	91	4.3
5. Reminders, racing greenery, shoreline	182	8.5
6. Forests	1036	48.2

Table 10.4 Classification of BPEJs into hydrologic groups of soils (HGS)

Occurring BPEJ	HGS	Occurring BPEJ	HGS
62041	Ca	72444	Cb
62044	Cb	73716	Ab
62414	Cb	73746	Ab
64168	Da	73846	Ab
64178	Db	74167	Da
65900	Da	74168	Db
72021	Ca	74177	Db
72024	Ca	74178	Db
72034	Ca	74189	Db
72041	Ba	74199	Db
72044	Ca	74911	Cb

(continued)

Table 10.4 (continued)

Occurring BPEJ	HGS	Occurring BPEJ	HGS
72051	Ca	74941	Cb
72054	Ca	75900	Da
72414	Cb	76701	Da
72441	Ca		

A, B, C, D—hydrologic groups of soils (HGS)
Index a—characterizes within a given HGS a higher retention capacity
Index b—characterizes within a given HGS a lower retention capacity
RWC—retention water capacity
Aa—RWC 50 mm and more
Ab—RWC 20–50 mm
Ba—RWC more than 100 mm
Bb—RWC less than 100 mm
Ca–RWC more than 80 mm
Cb–RWC less than 80 mm
Da–RWC more than 30 mm
Db–RWC less than 30 mm

10.4 Discussion

The submitted approach is based on a set of simple GIS methods. The main reason for this simplicity was the effort to make conflict analysis accessible to any GIS product used in urban planning practice. However, it is necessary to realize that high-

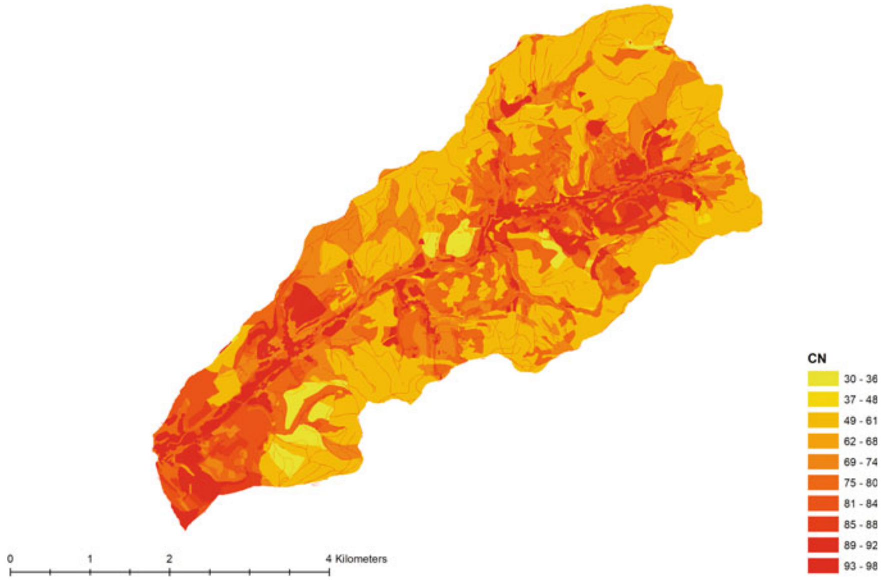

Fig. 10.2 Spatial distribution of CN-curve values in the Všeminka

Table 10.5 Total areas of the five classes of surface runoff for recent land use and a proposed scenario of precautions computed by the 'direct' outflow model per pixel

Surface runoff	Temperate rainfall of 4 mm			Storm rainfall of 20 mm		
	Interval (mm)	Recent area (ha)	Scenario area (ha)	Interval (mm)	Recent area (ha)	Scenario area (ha)
Very low	0–20	946.81	976.68	0–100	0	0
Low	20–40	620.12	761.96	100–200	0	0
Median	40–60	298.62	373.73	200–300	24.98	23.08
High	60–80	207.39	20.24	300–400	1278.29	1327.69
Very high	80–100	66.06	6.42	400–500	835.73	788.25

Table 10.6 Identification of areas with very high surface runoff in the catchment basin (shortened)

ID	River basin zone	Land use	Number of pixels	Area (ha)	Parcel number
5	1_denundation	Arable land	18	0.045	183
10	1_denundation	Road	3	0.0075	182.5
15	1_denundation	Watercourse	201	0.5025	1739
19	1_denundation	Swamp	136	0.34	56
21	1_denundation	Purposeful area	315	0.7875	0.56
46	1_denundation	Meadow	4	0.01	1388
44	1_denundation	Line greenery	3	0.0075	45
6	2_Transit-denudational	Deciduous forest	1	0.0025	365
7	2_Transit-denudational	Watercourse	189	0.4725	367
9	2_Transit-denudational	Swamp	50	0.125	751
12	2_Transit-denudational	Purposeful area	31	0.0775	75.23
35	2_Transit-denudational	Arable land	23	0.0575	85.56
38	2_Transit-denudational		12	0.03	96
40	2_Transit-denudational	Road	1	0.0025	1245
2	3_transit	Swamp	2	0.005	156
4	3_transit	Purposeful area	2	0.005	856
8	3_transit	Road	49	0.1225	66.1

quality digital data is crucial for the implementation of these GIS analyses. When inaccurate or incorrect data are used, the presented advantage of the model can lead to incorrect results and misleading interpretations. The precision of input data is very important in areas where the land use layer and the layers of environmental conditions overlap. The authors are aware of this fact, and that is why they strongly urge the observance of elementary GIS rules and the creation of data with the correct geometry, correct topology and correct attributes. The aim was not to develop a perfect hydrological model such as HEC, KINFIL or BASINS, but to provide a

Table 10.7 Designed optimal scenario of measures to increase retention capacity in the Všeminka basin

Location	Measures	Area (ha)
Infiltration zone of the catchment area		
Arable land	Grassed	38.8
Meadows and pastures	Wooded	74.1
Brownfields	Wooded	4.2
Forest stands	Improvement of species structure	4.2
River basin transport zone		
Arable land	Grassed	37.1
Meadows and pastures	Wooded	62.1
Brownfields	Wooded	6.2
Forest stands	Improvement of species structure	12.9
The catchment area		
Arable land	Grassed	37.1
Meadows and pastures	Change of technology	33.1
Brownfields	Wooded	20.6
Forest stands	Improvement of species structure	10.2
Total	Grassed	155
	Wooded	167.2
	Change of technology	33.1
	Improvement of species structure	27.3

simple tool for localizing the source of surface runoff, proposing measures to reduce it and simulating its effect in a commonly used program environment. Therefore, the absolute values achieved are rather informative, and more relevant information provides a comparison between scenarios or individual segments of the landscape. Despite these not so much ambitious objectives, this model has several significant features.

It works with a 5 m pixel, which represents a landscape cut of 25 m^2, allowing us to take into account the linear elements of the landscape (such as field paths) that are neglected in a number of models. The model not only takes into account their presence and type but also their spatial orientation towards the surface runoff direction [3]. The requirement is that the size of the element must be more than half of the pixel.

Another significant feature is the concept of multi-directional runoff. This concept more accurately simulates the real state of the landscape and is based on the assumption that the water flows from one point to several directions. This approach is based on Quinn's work (1991) and has so far been implemented in only a few models (e.g. TopModel, Usle 2d). On the other hand, the vast majority of models work with the drain concept most steeply, and if the results are compared, the sub-values will vary.

10.5 Conclusions

Flood areas have been used intensively for a number of social and economic activities these days, and so floods can easily damage property and public health within these areas. One possible solution is to limit human activities in floodplains; the second one is a prediction based on hydrologic modelling of floods and spatial conflicts in GIS. Planning materials and planning documentation are the only respected documents for urban development in the Czech Republic, but modern tools for spatial modelling are only very closely used during the creation of these documents. Presented approach (model) is an example of GIS implementation in the process of creating these documents. The model was tested in practice, and it helped to find spatial conflicts. The outputs of GIS analyses of the model were raster data sets, hydrographs and tables. The model can take into account the current state and applied measures to reduce flood risk on a very detailed scale.

LOREP is a useful tool for identifying and localizing areas with low flood regulation capabilities because it works in areas with a very high or high direct runoff. It can suggest different scenarios and assess them. The catalogue of remedies and non-technical solutions in the landscape is a part of the model, and these remedies can then be selected for an increase in flood control capabilities in the watershed. LOREP can be used for large or small watersheds, and its great advantage is that it is a part of GIS. Wide implementation of GIS to planning practice will be possible only if legislation will require such approach.

10.6 Recommendations

The modelling of the water retention function is currently subjected to new challenges. In the context with the ongoing climate change, with irregular alternation of flash abundant rainfall and long periods of drought, it is essential to well describe the current and future state of the landscape.

The following recommendations should be followed when modelling a water retention function: (i) work with a model that best simulates real water behaviour in the landscape (it means that the model works with an advanced multi-flow algorithm to simulate real water movement in the landscape); (ii) use a model with an advanced iteration algorithm to calculate infiltration, which can estimate at each step whether retention capacity is already achieved or not and iii) use the appropriate drain equation according to the evaluation of this state.

Static (GIS) data describing the state of the landscape should be integrated with sensor data (e.g. snow supply and soil moisture) to update hydrological/hydropedological conditions. Digital representations of all landscape components (terrain, land use and soil) should be current and at the same scale and for the same time period. The scale should be detailed enough to capture the small line elements in the landscape and their orientation towards the direction of the surface runoff. For the conditions of the Czech Republic, it is appropriate to scale 1:10,000. To identify the problem areas, it is necessary to work with the model in a raster environment in order to divide the studied area into sub-watersheds, not exceeding 25 m^2. This tool is really useful in the situation when almost all plots of concentrated surface runoff should be identified and multi-directional runoff, including runoff along small line elements, should be assessed.

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