Implementation of a rainfall-runoff model in TELEMAC-2D

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***Abstract*— Since version v6p2 it is possible to model rain or evaporation in TELEMAC-2D and TELEMAC-3D. However, this feature does not include dynamic modelling of the infiltration processes during a rainfall event. In Sweden, 2D hydraulic models are starting to be widely used for rainfall simulations with applications in urban planning and sewage system design, natural hazards risk assessments (flooding, debris-flow) and in the mining industry (tailing dams). In all of the above, infiltration can be of utmost importance. The possibility to dynamically model the infiltration process during a rainfall event will therefore increase the suitability of 2D hydraulic models for such applications. With that objective, a rainfall-runoff model has been implemented in TELEMAC-2D. The model is based on the Method of Abstractions, developed by USA's Soil Conservation Service, in which the infiltration potential is characterized by a coefficient called Curve Number (CN). This coefficient is a function of four major runoff properties (hydrological soil groups, land use, hydrologic surface condition of native pasture and antecedent moisture conditions). The Curve Number runoff model implemented in TELEMAC-2D offers the possibility to define spatially varying CN values at each computational node. The model also includes the possibility to account for the actual terrain slope by adjusting the CN values locally. Finally, options making it possible to read a block-type hyetograph from a formatted data file as well as applying a so-called Chicago Design Storm hyetograph from Intensity-Duration-Frequency equation parameters have been implemented. The Curve Number runoff model will be available in the next release of the open TELEMAC-MASCARET suite (version v7p2).**

I. INTRODUCTION

Since version v6p2 it is possible to model rain or evaporation in TELEMAC-2D and TELEMAC-3D. However, this feature does not include dynamic modelling of the infiltration processes during a rainfall event. In Sweden, 2D hydraulic models are starting to be widely used for rainfall simulations with applications in urban planning and sewage system design, natural hazards risk assessments (flooding, debris-flow) and in the mining industry (tailing dams). In all of the above, infiltration can be of utmost importance. The possibility to dynamically model the infiltration process during a rainfall event will therefore increase the suitability of 2D hydraulic models for such applications. With that objective, the Curve Number runoff model has been implemented in TELEMAC-2D.

This paper is articulated in three parts. In the first part, the Curve Number runoff model is presented. The second part describes how the model and its options have been implemented in TELEMAC-2D, the different methods for rainfall definition and a new validation case. Finally, an example of application is presented.

II. THE CURVE NUMBER RUNOFF MODEL

A. *Method*

The Curve Number runoff model, also known as the SCS Method of Abstractions, has been developed from 1954 by USA's Soil Conservation Service (SCS). This method, which is widely used in the world, aims at computing abstractions from storm rainfall using a spatially and temporally lumped infiltration loss model. It gives best results in agricultural watersheds with negligible baseflow [1].

The conversion from rainfall to runoff can be expressed by the following conservation equation:

$$P = P_e + F \tag{1}$$

With P the rainfall depth (mm), P_e the runoff depth (mm) and F the hydrologic abstractions (mm).

The aim of runoff modelling is to assess the hydrologic abstractions F which are composed of (i) interception storage (vegetation foliage…), (ii) surface storage, (iii) infiltration, (iv) evaporation and (v) evapotranspiration. For short-term storm modelling, which is the Curve Number runoff model's field of application, abstractions due to infiltration are largely predominant over other forms which are then disregarded [1].

Runoff analysis has shown that runoff begins after that a certain amount of rainfall, called "initial abstraction", is abs-

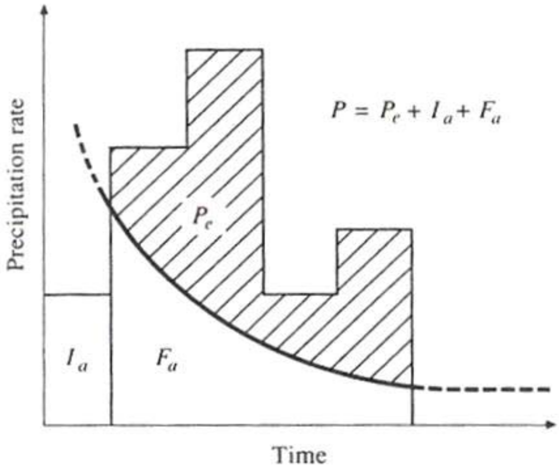

Figure 1. Variables in the Curve Number runoff model [3].

tracted as interception, infiltration and surface storage [2]. The conservation equation can also be written as:

$$P = P_e + I_a + F_a \tag{2}$$

With I_a the initial abstraction (mm) and F_a the hydrologic abstraction (mm) corresponding to infiltration and also called "continuing abstraction". The different variables in the Curve Number runoff model are illustrated in Fig. 1.

The Curve Number runoff model is based on the assumption that retention is proportional to runoff:

$$\frac{F_a}{S} = \frac{P_e}{(P - I_a)} \tag{3}$$

With S the potential maximal retention (mm). The expression of the runoff P_e can then be obtained by combining (2) and (3):

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \; for \; P > I_a$$

$$P_e = 0 \; for \; P \le I_a \tag{4}$$

This expression is the main equation of the Curve Number runoff model and is based on two parameters, I_a and S. A relation between I_a and S was developed using rainfall and runoff data from experimental watersheds [2]:

$$I_a = \lambda \cdot S \tag{5}$$

The coefficient λ, known as the initial abstraction ratio, has been originally defined as 0.2 (-) [2]. It can be noted that more recent studies have pointed out that this value is probably high, as presented in the next section. The runoff equation relies then on only one parameter, the potential maximal retention S. It is however difficult to estimate this parameter which is function of geological and hydrological conditions and which theoretically varies between 0 and infinity. For practical reasons, the Curve Number (CN, dimensionless) has then been defined as:

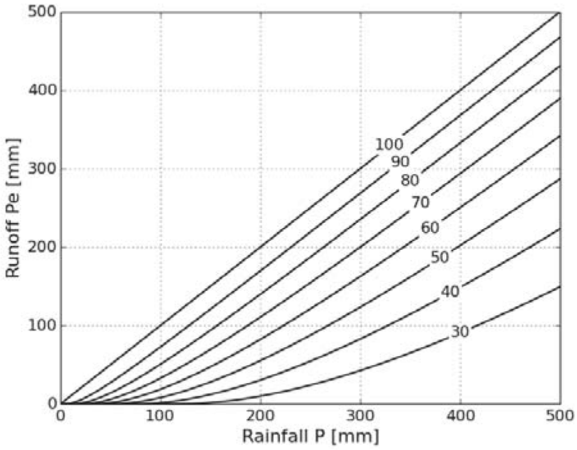

Figure 2. Solutions of the runoff equation (4) for CN values varying between 30 and 100 and for λ = 0.2.

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10\right) \tag{6}$$

Curve Number values vary between 0 (infinite potential maximal retention i.e. no runoff) and 100 (no retention i.e. no infiltration) and are function of geology, land use and antecedent moisture conditions. Solutions of (4) for CN values varying between 30 and 100 and for λ = 0.2 are presented in Fig. 2.

The SCS has defined Curve Number values for different types of land use classes and for four different hydrological soil groups: Group A (deep sands, deep loess and aggregated silts), Group B (shallow loess, sandy loams), Group C (clay loams, shallow sandy loams, soils low in organic content and soils usually high in clay) and Group D (soils that swell significantly when wet, heavy plastic clays and certain saline soils) and for three type of hydrologic surface condition of native pasture (poor, fair, and good). These values, which are presented in tables and are available in handbooks (for example [3, 4]), have been determined for an initial abstraction ratio λ = 0.2 and for normal antecedent moisture conditions (referred as AMC II) are referred as CN(II).

For dry antecedent moisture conditions (AMC I, lowest runoff potential) and wet antecedent moisture conditions (AMC III, highest runoff potential), CN(II) values can be converted with the following equations (also illustrated in Fig. 3) [3]:

$$CN(I) = \frac{4.2 \cdot CN(II)}{10 - 0.058 \cdot CN(II)} \tag{7}$$

$$CN(III) = \frac{23 \cdot CN(II)}{10 + 0.13 \cdot CN(II)} \tag{8}$$

The antecedent moisture condition classes has been initially defined based on the 5-day antecedent rainfall for the dormant and growing season [2, 3]. However, more recent analyses have shown that there is no apparent relationship between antecedent rainfall and CN values [5]. Despite a

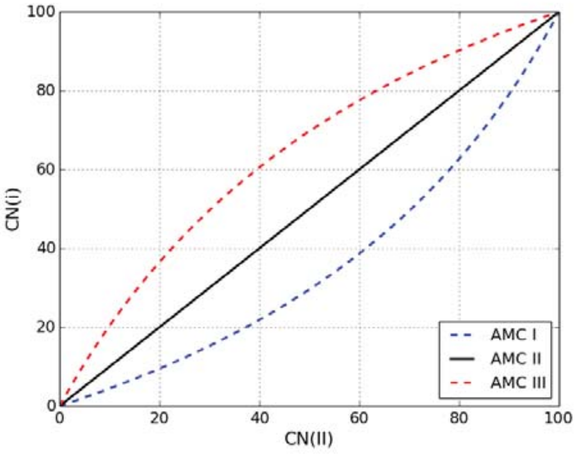

Figure 3. Curve Number conversion based on antecedent moisture condition classes (AMC).

relative lack of guidance, antecedent moisture condition classes can be used as a calibration or design parameter.

Although being a lumped method, the Curve Number runoff equation (4) can be time distributed to simulate infiltration during a storm. Equations (2) and (3) can be combined to obtain the accumulated continuing abstraction F_a [3, 5]:

$$F_a = \frac{S \cdot (P - I_a)}{P - I_a + S} \quad for\ P > I_a$$

$$F_a = 0 \quad for\ P \leq I_a \tag{9}$$

With P being the accumulated rainfall depth (mm) at a given time step. The corresponding accumulated runoff depth P_e can then be determined using (2).

B. *Reanalysis of the initial abstraction ratio*

The initial abstraction ratio was analysed through rainfall-runoff data measured on 307 watersheds or plots in the USA [6]. The results have shown that the ratio λ varies from storm to storm and that the original value of 0.2 is unusually high. The study concluded that the value of λ can be re-estimated to 0.05 and that more than 90% of the values were lower than 0.2. Changing the initial abstraction ratio from the original method implies that the potential maximal retention and hence the Curve Number should be adjusted. The study proposed a relationship giving CN(II) values expressed in terms of λ = 0.05 as a function of the standard CN(II) values expressed in terms of λ = 0.2 (see also Fig. 4):

$$CN(II)_{\lambda=0.05} = \frac{100}{1.879 \cdot (100/CN(II)_{\lambda=0.2} - 1)^{1.15} + 1} \tag{10}$$

This new formulation implies that runoff occurs earlier than with the standard method (λ = 0.2). The greater effect is found on storms with low P/S ratios, i.e. for either small storms or storms with low CN values, for example forest, for which the peak discharge tends to increase. For a more detailed analysis, please refer to [6].

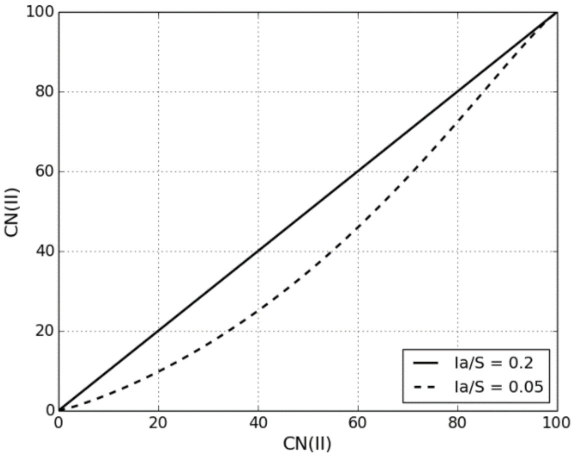

Figure 4. Curve Number conversion for an initial abstraction ratio λ = 0.05.

C. *Effect of steep slopes*

The terrain slope has not been incorporated in the original Curve Number runoff model which is believed to be valid primarily for low slope terrains. However, it has been demonstrated that increasing terrain slopes generate increasing runoff volumes [7]. An experimental study performed on a watershed located in the Loess Plateau of China has proposed a relation to adjust the standard Curve Number for slopes between 0.14 and 1.4 m/m [7]:

$$CN(II)_{\alpha} = CN(II) \cdot \frac{322.79 + 15.63 \cdot \alpha}{\alpha + 323.52} \tag{11}$$

With α the terrain slope in m/m (0.14 ≤ α ≤ 1.4). The standard CN values can then be increased by up to approximatively 6% for a slope α = 1.4.

D. *Remark*

It has been common practice to use the Curve Number runoff model using a weighted CN value over the whole watershed. This was done mainly to limit the number of calculations. The use of computers with the possibility to define several CN values within the watershed based on local geological and hydrological characteristics has removed this constraint. As the runoff depth does not evolve linearly with the potential maximal retention (and therefore the Curve Number), see (4), differences will be observed between the two methods on a same watershed (weighted CN value or spatially defined CN values).

E. *Advantages and disadvantages of the Curve Number runoff model*

In [1], V. Ponce and R. Hawkins have done a critique of the Curve Number runoff model listing up its advantages and disadvantages. The most important points are recalled hereafter.

Advantages:

- The method is simple, stable, predictable and based on empirical data.
- It relies on only one parameter (CN) which varies as a function of four major runoff properties (hydrological soil groups, land use, hydrologic surface condition of native pasture and antecedent moisture conditions).
- It is well established and used worldwide.

Disadvantages:

- The method was developed using regional field data from the United States. Certain caution is therefore required for use in different regions.
- The results are very sensitive to the antecedent moisture condition classes. Furthermore, there is no clear guidance on how to determine which class to use.
- The method assumes an initial abstraction ratio λ = 0.2 which was shown to be overestimated (see above).
- The method should be used with caution on large watersheds (> 250 km^2).

III. IMPLEMENTATION IN TELEMAC-2D

A. *Overview*

In TELEMAC-2D, rain or evaporation is modelled as a source term implemented in subroutine `prosou.f`. The Curve Number runoff model has been implemented in a new subroutine called `runoff_scs_cn.f` (available from version v7p2). The model is activated thanks to a new keyword RAINFALL-RUNOFF MODEL whose value should be set to 1 (default is 0, no runoff model) and assuming that the keyword RAIN OR EVAPORATION is set to YES. The input data consist in rainfall and the standard CN(II) values that can be defined at each node of the computational domain.

The standard method for defining the CN(II) values is a spatial interpolation performed from a user defined set of points defining polygons with constant CN(II) values. This data is to be provided in a formatted data file. Note that each polygon must have unique point coordinates (polygons cannot share vertices with identical coordinates).

CN values can also be defined directly in the geometry file as an additional variable. This variable is read by TELEMAC-2D when the keywords NAMES OF PRIVATE VARIABLES and NUMBER OF PRIVATE ARRAYS are included in the steering file. Examples of application for both methods are provided in a new validation case (see next section).

The antecedent moisture conditions can be defined with the new keyword ANTECEDENT MOISTURE CONDITIONS (1: AMC I, dry antecedent moisture conditions; 2: AMC II, normal antecedent moisture conditions [default]; 3: AMC III, wet antecedent moisture conditions). When choosing the option 1 or 3, CN(II) input values are converted to either CN(I) or CN(III) using (7) and (8).

The user can also choose between the original initial abstraction ratio (λ = 0.2) and the revised formulation (λ = 0.05) with the new keyword OPTION FOR INITIAL ABSTRACTION RATIO (1: λ = 0.2 [default]; 2: λ = 0.05). When choosing the option 2, CN(II) input values are converted using (10).

Finally, it is possible to adjust CN(II) values to account for steep slopes using (11). This option should be activated manually directly in `runoff_scs_cn.f` (local variable `STEEPSLOPECOR`, not activated by default).

The Curve Number runoff model requires that the tidal flats option is activated (TIDAL FLATS = YES).

B. *Options for rainfall definition*

Rainfall can be defined in three different ways in the Curve Number runoff model. The standard method consists in using a rainfall with constant intensity defined by the existing keyword RAIN OR EVAPORATION IN MM PER DAY (method activated by default). A new keyword has been introduced to define the duration of rain (or evaporation): DURATION OF RAIN OR EVAPORATION IN HOURS (units: hours, default is infinite). This keyword can also be used with the standard rain or evaporation function (without runoff model).

Rainfall can also be defined by a user specified block-type hyetograph giving the rainfall depth (mm) between two consecutive times provided in a formatted data file.

Finally, rainfall can also be defined as a so-called Chicago Design Storm (CDS) hyetograph computed automatically from user defined Intensity-Duration-Frequency (IDF) parameters.

The IDF relationship used is [3]:

$$i = \frac{a}{t^b + c} \tag{12}$$

With *i* the rainfall intensity over a duration *t* (mm/h), *t* the rainfall duration (hours), *a*, *b* and *c* are the IDF parameters. The instantaneous rainfall intensity *i* (mm/h) is then obtained from the following expression [3]:

$$i = \frac{a \cdot \left((1-b) \cdot t_R^b + c \right)}{\left(t_R^b + c \right)^2} \tag{13}$$

With t_R the time relative to rainfall peak (hours):

$$\begin{aligned} t_R &= \frac{t_{peak} - t}{R} \quad for\ t < t_{peak} \\ t_R &= \frac{t - t_{peak}}{1-R} \quad for\ t \geq t_{peak} \end{aligned} \tag{14}$$

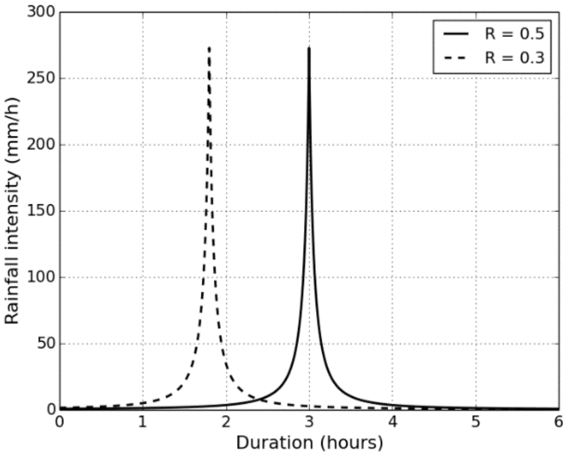

Figure 5. Example of CDS-type hyetographs (a = 60.0 – b = 0.97 – c = 0.22) expressed in rainfall intensity (mm/h).

With t the current time step (hours), t_{peak} the time of the rainfall peak (hours) and R the peak decentring parameter (dimensionless, varies between 0 and 1). The time of peak is defined as:

$$t_{peak} = R \cdot t_{rainfall} \tag{15}$$

With $t_{rainfall}$ the duration of the rainfall event provided by the new keyword DURATION OF RAIN OR EVAPORATION IN HOURS.

Examples of CDS-type hyetographs are given in Fig. 5 for a rainfall duration of six hours and with two different decentring parameters (R = 0.5, symmetrical hyetograph and R = 0.3).

Block-type or CDS-type hyetograph can be chosen manually directly in `runoff_scs_cn.f` (local variable `RAINDEF`).

Evaporation is not supported by the Curve Number runoff model.

C. Validation case

A new validation case called “pluie” has been added to the TELEMAC-2D library and will be available from version v7p2 (…/examples/telemac2d/pluie). Three examples are provided with (i) a classic rainfall defined by a constant rainfall intensity without runoff model, (ii) a classic rainfall defined by a constant rainfall intensity with Curve Number runoff model using CN(II) values interpolated from a set of points provided in a formatted data file and (iii) a rainfall defined by a hyetograph read from a formatted data file with Curve Number runoff model using CN(II) values stocked in the geometry file as an additional variable.

The classic rainfall is defined using the existing keyword RAIN OR EVAPORATION IN MM PER DAY = 100.0 and for a duration of 6 hours (DURATION OF RAIN OR EVAPORATION IN HOURS = 6.0) so that the total rainfall depth is 25 mm. The hyetograph defined in the last example has an irregular time distribution but has the same total rainfall depth.

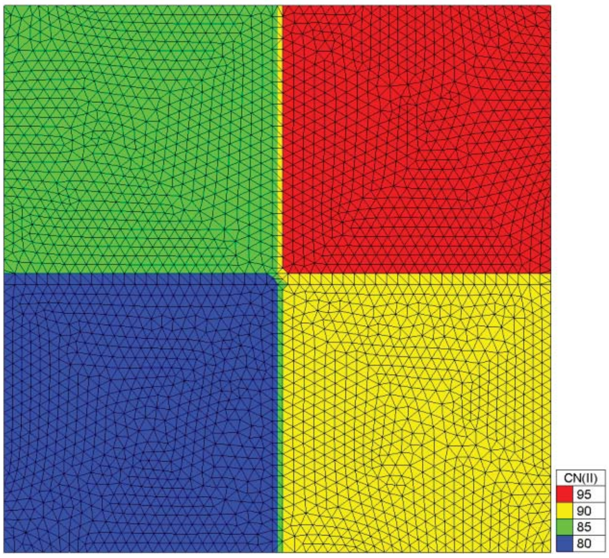

Figure 6. Computational domain used for the validation case with spatial repartition of CN(II) values.

The Curve Number runoff model is used with default settings (ANTECEDENT MOISTURE CONDITIONS = 2 and OPTION FOR INITIAL ABSTRACTION RATIO = 1).

The model geometry is a square with a side length of 100 meters composed of 5412 triangular elements with no open boundaries and with a constant bathymetry. The computational domain is divided in four parts with CN(II) values of 80, 85, 90 and 95, see Fig. 6. All the examples are run over a simulation period of 8 hours with a time-step of 200 seconds.

Results from the first example show, as expected, a constant water depth of 0.025 m at the end of the simulation corresponding to the total rainfall depth applied (no infiltration).

Results from the second and third examples show similar runoff depths at the end of the simulation for each CN(II) value. This result is expected since the rainfall depth is only function of the CN(II) values and of the total rainfall depth. The runoff depths are saved as an additional user variable in the result files named “ACC. RUNOFF”. The final runoff depths obtained from the simulations for each CN(II) value are presented in Table I.

TABLE I. TOTAL RAINFALL AND RUNOFF DEPTHS FOR THE VALIDATION CASE.

Rainfall (mm)	**Runoff (mm)**			
	CN(II) = 80	***CN(II) = 85***	***CN(II) = 90***	***CN(II) = 95***
25.0	2.0	4.2	7.9	14.0

Their values are identical to the analytical solutions of (4) with a precision of 10^{-9} m. The CPU times of the provided examples are a few seconds in scalar mode on a laptop machine.

D. Additional computational cost

The additional computational cost of the new Curve Number runoff model has been estimated by comparing CPU times of the following simulations:

- Classic rainfall defined by a constant rainfall intensity without runoff model.
- Classic rainfall defined by a constant rainfall intensity with Curve Number runoff model used with CN(II) = 100 over the whole computation domain. The CN values are assigned using the default method, for instance a spatial interpolation from a set of points provided in a formatted data file.
- Similar case as above but with CN(II) values stocked and read from the geometry file.

Using CN(II) = 100 (i.e. no infiltration) ensures that the rainfall depth added in the domain at each time step is identical for all the simulations which makes it possible to assess the computational cost added by the new model only independently of the hydrodynamics conditions.

The model geometry used is a square with a side length of 1000 meters composed of 581 130 triangular elements with no open boundaries and with a constant bathymetry. The simulations have been performed using the same settings than those defined in the validation examples except for the time step which has been chosen to 20 seconds. The machine used was a DELL laptop (Windows 7 64-bit) with a processor of 2.5 GHz and 16 GB of RAM. The Fortran compiler used was gfortran version 4.7.0. Simulations have been performed in scalar mode. Results are presented in Table II.

TABLE II. ESTIMATION OF THE ADDITIONAL COMPUTATIONAL COST.

Simulation	**CPU time**	**Cost**
No runoff model	1407 s	-
CN runoff model with spatial interpolation of CN(II) values	1515 s	7.7%
CN runoff model with CN(II) values stocked in geometry file	1417 s	0.7%

Results show that the CPU time of the reference case (no runoff model) is increased by 7.7% when using the default method for assigning the CN(II) values at each node (spatial interpolation) whereas the additional computational cost can be considered as negligible when CN(II) values are stocked and read from the geometry file (0.7%). The cost generated by the spatial interpolation step is function of the model size and simulation duration.

IV. EXAMPLE OF APPLICATION

The Curve Number runoff model has been used to model runoff conditions in a watershed located on the eastern coast of the Lake Vättern in Sweden, approximatively 8 km in the North-East of the city of Jönköping. Lake Vättern's eastern coast is characterized by 200 to 300 m high hills with locally steep slopes along the shoreline. The hills are mainly covered by forest and by agricultural land. Soils are composed mainly of sandy to silty moraine. Bedrock outcrops are present in the steeper slopes. The drainage system is composed of ditches. In the southern part of the watershed, where the steeper slopes are located, the ditches transform into ravines characterized by bed slopes up to 30-35 degrees. The time of concentration of these ravines is approximatively 30 minutes. The aim of the study was to assess the runoff potential in the watershed as part of a debris-flow risk assessment and to define flooding maps.

A TELEMAC-2D model covering the 5 km^2 watershed has been set up with element sizes varying between 1 and 2 m and totalling approximately 2 800 000 elements. Model boundary on land corresponds with the watershed's bound. The model has one open boundary, Lake Vättern, defined with a constant water level (mean water level). Eight pipes or culverts located under the existing roads have been included in the model.

One of the main difficulties of two-dimensional rainfall modelling is the definition of bottom friction as runoff is typically characterized by small water depths (so-called "sheet flow"), usually much smaller than the mesh size. An interesting approach would be to use a friction coefficient defined as a function of bottom asperities' submergence ratio [8, 9]. However, in this application, friction was modelled using the classic Strickler equation and with assumed coefficients of 5 m$^{1/3}$/s for natural terrain [10] and of 50 m$^{1/3}$/s for hard surfaces. For such applications it can be considered that the Strickler coefficients for natural terrains are independent of the land use and therefore of the CN values.

Rainfall was defined as Chicago Design Storm (CDS) hyetographs with a duration of 6 hours for return periods between 10 and 500 years. A frequency analysis has been performed on data from four meteorological stations located

Figure 7. Repartition of CN(II) values over the computational domain.

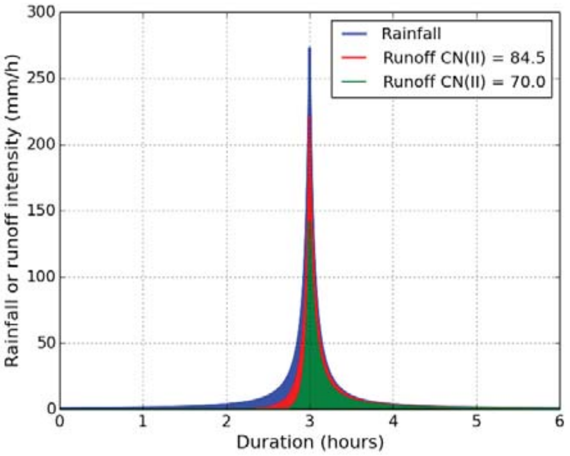

Figure 8. Rainfall hyetograph and corresponding runoff hyetographs for CN(II) = 70 and 84.5 and AMC III expressed in intensity (mm/h). The rainfall hyetograph has been defined using similar IDF parameters than on Fig.5.

around the watershed in order to define Intensity-Duration-Frequency (IDF) curves. Finally, these curves have been approximated with three-parameter IDF equations (11) by least-square fitting. Rainfall was defined as symmetrical hyetographs (peak decentring parameter $R = 0.5$).

CN values have been defined for three land use types: (i) forest, (ii) agricultural land and (iii) roads and other types of hard surfaces or lakes. The CN(II) values were defined for the hydrological soil groups C and D and the antecedent moisture conditions were considered to be wet (AMC III, highest runoff potential). The model was used with the standard initial abstraction ratio formulation ($\lambda = 0.2$). The CN(II) values have also been corrected to account for steep slopes.

The CN(II) values were eventually calibrated against estimations of specific discharges for 100-year return period flow available in the same area (no hydraulic calibration data was available). The simulations have been performed with CN(II) values of (i) 70 for forest, (ii) 84.5 for agricultural land and (iii) 100 for roads and other types of hard surfaces or lakes, see Fig. 7.

An example of calculated 100-year return period runoff hyetographs for CN(II) = 70 and 84.5 and for AMC III is presented on Fig. 8. The corresponding rainfall and runoff depths, computed with (4) to (8), are presented in Table III.

TABLE III. TOTAL RAINFALL AND RUNOFF DEPTHS FOR THE HYETOGRAPHS OF FIG. 8.

Rainfall (mm)	**Runoff (mm)**	
	CN(II) = 70	***CN(II) = 84.5***
61.0	26.8	42.0

V. SUMMARY AND CONCLUSIONS

A runoff model has been implemented in TELEMAC-2D in order to take spatially varying infiltration processes into account during storm rainfall modelling. The model is the Curve Number runoff model, also known as the SCS Method of Abstractions, which has been developed from 1954 by USA's Soil Conservation Service (SCS) and is widely used worldwide. The main advantage of this model relies in its simplicity since infiltration is defined by only one parameter function of four major runoff properties (hydrological soil groups, land use, hydrologic surface condition of native pasture and antecedent moisture conditions). The model has been implemented along with two options regarding the definition of the initial abstraction ratio and a correction to account for steep slopes. Rainfall can be defined in three different ways (with a constant rainfall intensity, with a user defined hyetograph or with a so-called Chicago Design Storm hyetograph based on a three-parameter Intensity-Duration-Frequency equation). The Curve Number runoff model will be available in the version v7p2 of the TELEMAC-MASCARET suite along with a validation case.

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