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Presentation of a Hydrological Approach for the Assessment of Surface Runoff through Remote Sensing

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Abstract: In this study a physically based hydrological model coupled with the SCS curve number method is presented to assess the runoff changes due to land-use changes. In order to approach a reasonable result in hydrologic modelling, satellite-based remote technologies are used to extract land surface parameters. For known rainfall event, future changes in land use can also be incorporated in the model once digital database is available and the change in runoff hydrographs can be estimated. The study clearly demonstrates that the integration of spatial data and the application of a physically based model in a remote sensing environment provide a powerful tool for the assessment of an effect due to land-use change.

Key words: Runoff hydrographs, land-use changes**,** urbanization, remote sensing, hydrological model, SCS curve number.

Introduction

The Seybousse catchment located in eastern Algeria has undergone rapid urbanization and tremendous economic growth during the past few years. Infrastructure development has further enhanced the land-use change process in the area. Increased impervious surfaces are a common cause of increased peak-runoff volumes. This reality is due, in urban areas, to the replacement of a natural hydrographic network using sinuous routes, not very sloping, and to an over-sized urban stormwater drainage system which is equipped with a comfortable slope to decrease its diameter and thus its cost. Thus the drainage network causes a reduction in the flow way towards the catchment outlet. River basin management poses big challenges especially in developing countries because of lack of continuous data particularly streamflow data that require automatic recording instruments to acquire. Remote sensing technology can augment the conventional methods to a great extent in rainfall-runoff studies. The role of remote sensing in runoff calculation is generally to provide a source of input data or it is used as an aid for estimating equation coefficients and model parameters. Remote sensing can be incorporated into the system in a variety of ways: as a measure of land use and for impervious surfaces, for providing initial conditions for flood forecasting, and for monitoring flooded areas (Schultz and Edwin, 2000; Shrestha, 2002). One of the options for the use of RS is to improve the estimation of watershed parameters like Curve Number for a drainage basin with the widely used SCS model from its land-use data and digitized soil map. In the past 30 years, the SCS method has been used by a few researchers because it gives consistently usable results for runoff estimation (Sharma and Kumar, 2002; Chandrmohan and Durbude, 2001; Sharma et al., 2001). The United Nations has estimated that the level of urbanisation for developed countries is about 73% (Sunil, 2000). Bad land-use management practices are thought to be the cause of increased flooding. It is thus very important to assess the runoff changes due to land-use changes.

Methodology

Physical Model

A watershed is the area covering all the land that contributes runoff water to a common point. It results from the superposition of a natural hydrographic network and various anthropic constructions, which modify the water cycle. These modifications have been taken into account until now in the various models via the value of the imperviousness coefficient. This coefficient was introduced differently into several models (Mosini et al., 2000; Brun and Band, 2000; Wittenberg, 1974). The conversion of rain to runoff on a catchment area is often apprehended through the theory of the unit hydrograph, which has known various developments since its introduction. This approach is largely used successfully in rural hydrology and opens the way to spatially distributed modelling. The model used in this study is composed by two parallel cascades of linear reservoirs (Wittenberg, 1974). The distribution of the rain solicitation is carried out by the intermediary of the dividing factor *F*. The total outflow of the whole catchment area is obtained by superposition of the two partial flood waves. The response of the system is given by the following relation:

$$u(t) = F\left\{\frac{1}{k_1(n_1-1)}\left(\frac{t}{k_1}\right)^{(n_1-1)} * e^{-t/k_1}\right\} + (1-F)\left\{\frac{1}{k_2(n_2-1)}\left(\frac{t}{k_2}\right)^{(n_2-1)} * e^{-t/k_2}\right\} \quad (1)$$

As we can note, the parallel cascade model is characterized by the following five parameters:

- k_1 : storage constant of the first linear reservoir cascade,
- k_2 : storage constant of the second linear reservoir cascade,
- n_1 : number of linear reservoirs of the first cascade,
- n_2 : number of linear reservoirs of the second cascade and
- F : dividing factor between the cascades.

The runoff process in mixed catchment is divided into the discharge from impervious surface and the discharge from pervious areas. Therefore, only two parallel reservoirs are used, in which different storage effects are taken into account. In this case, only three parameters are to be determined k_1, k_2 and *F*. In accordance with the recommendations of DVWK (1980), the two parameters k_1 and k_2 are determined by using the equations (2) and (3):

$$k_1 = 0.731 \quad (2)$$

$$k_1 = 3.04 \times k_1^{1.29} \quad (3)$$

where l_F is the longest flow path length and *I* the slope.

In order to determine *F*, the following relation is proposed:

$$F = 2.41\left(l_F / \sqrt{I}\right)^{-0.574} \quad (4)$$

Materials and Methods

The Upper Seybousse maritime watershed, that is a part of the catchment area of Seybousse, lies in the district of Annaba in Eastern Algeria. It is located at 7,701366 to 7,805208 E longitude and 36,468339 to 36,883900 N latitude with an elevation ranging 10-750 m above MSL (mean sea level) and extends over a total area of 246.421 km^2. The multispectral image used in this study is from sensors HRV2 in spectral mode XS of the satellite SPOT4. It is extracted from the scenes 059-276 and 059-277 acquired on May 19, 2000 at 10:40:32 am. This image of three spectral channels (R, V, NIR) of spatial resolution 20 m × 20 m and size 3005 × 3717, covers the Seybousse basin situated in the east of Algeria.

The area is characterized by a diversity of surface qualities. It also contains the city of Annaba located at 600 km to the east of Algiers with a dense urban area gathering some cities and villages near agriculture and industry. Two methods of classification are commonly used: Unsupervised and Supervised. In this framework we limit ourselves here, with the methods of supervised classification, which is much more accurate for mapping classes, but depends heavily on the cognition and skills of the image specialist. Image to image registration was performed using the registered topographic maps. From the scanned map boundaries of different soil textures were digitized carefully and the polygons representing various soils were assigned and flood filled with different colours for identification. In the present investigation an attempt is made to establish the SCS Curve Number from the Algerian remote sensing digital database for Seybousse maritime watershed. The Soil Conservation Service (SCS) Curve Number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture. The tabulated CN values are for normal soil with a moisture condition, which is referred to as Antecedent Moisture Condition II (AMC-II). AMC-I has the lowest runoff potential and the watershed soils are dry. AMC-III has the highest runoff potential as the watershed is practically saturated from antecedent rainfall. The individual CNs were found verifying the hydrological soil group by overlaying the soil and land-use/land-cover map. Different gray level values were assigned to different soil texture while preparing the maps. Four hydrologic soil groups, A, B, C and D, were considered for the basic classification of soils of the watershed. The soils of group A are of a low runoff potential, a high infiltration rate, and a high rate of water transmission. The soils of group B are of a moderate infiltration rate, moderately well drained to well drained; the soils of group C are of moderately fine to moderately coarse textures, with a moderate rate of water transmission. And the soils of group D are of slow infiltration and a high runoff potential. Based on the hydrological soil group, the maximum area of the Upper Seybousse maritime watershed was observed to be under hydrological soil group B (49.5%) followed by (28.4%) D and (13.6%) group C and at last (8.5%) group A. Similarly, the study area was identified in the six major land use classes as shown in Table 1. A CN is ascribed to the area with a particular soil type and land use; it is multiplied by the area covers and its weighted CN value is found out. This CN value is used in Equation (5) and the value of the effective rainfall P_e is obtained. The results are summarized in Table 2.

Table 1: Land use/cover classes present in the study area

Land use	*Surface [km²]*	*% of total area*
Cultivated land (good crop)	53.4095	21.67408622
Forest	88.761	36.02006323
Paved areas (roads, driveways, parking lots, roofs)	15.189	6.163841556
Habitat (township and villages, industrial)	73.9415	30.00616831
Swamp	2.704	1.097309077
Fallow	12.416	5.038531619
Total	246.421	100

Table 2: Determination of the SCS variables

Expressions	*AMC I*	*AMC II*	*AMC III*
CN Value	66.8	82.4	92.6
S	126.4 mm	54.2 mm	20.2 mm
I_a	25.3 mm	10.8 mm	4.0 mm
P_e	7.8 mm	24.0 mm	41.9 mm

$$P_e = \frac{[(P/25,4) - (200/CN) + 2]^2}{(P/25,4) + (800/C_N) - 8} \times 25.4 \text{ in mm} \quad (5)$$

where P_e = accumulated precipitation excess at time t; P = accumulated rainfall depth at time t; I_a = the initial abstraction (initial loss); and S = potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation. Initial abstractions are water losses which occur prior to runoff and are thus subtracted from the total rainfall available for either soil retention or quick response. To remove the necessity for an independent estimation of initial abstraction, a linear relationship between I_a and S was suggested by SCS (US Department of Agriculture, 1986) as:

$$I_a = \lambda . S \quad (6)$$

where λ is an initial abstraction ratio. In this study, curve number and, particularly, antecedent moisture were investigated for describing outlet response of a Seybouse maritime basin. For simplicity, initial abstractions were assumed to be 0.2S, with further investigation left for future study. The T_c is very often defined as the time required for a particle of water to travel from the most hydrologically remote point in the watershed to the point of collection. There are several methods available for calculating T_c, one of which is the Lag Method:

$$T_{lag} = \frac{2.587.L^{0.8}.\left(\frac{1000}{CN} - 9\right)^{0.7}}{1900.H^{0.5}} \quad (7)$$

The somewhat more difficult parameter is the slope. To determine the average watershed slope, first a slope map has to be created. The slope map is calculated by filtering the DEM of the catchment area in x and y directions. In this framework the main object is to study what effect the design flood produced by the 100 years, 24-hour rainfall will have in bulk land-use changes. In a first stage the method was applied for the actual land cover conditions (Figure 1), then after the introduction of the hypothetical changes of land use (Figure 2) and this for the three initial cases of initial moisture conditions AMC I, AMC II and AMC III.

The results show clearly the influence of the initial rates of soil saturation on the runoff. The hydrograph evolution is in agreement with the field reality. A rapid rise and a relatively slower regression could be reproduced. In a second stage the aim is to compare the hydrographs before and after the introduction of a change in land use. An example is presented for the initial

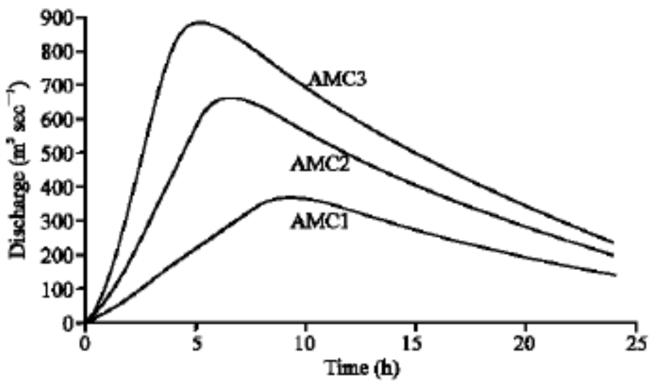

Figure 1: Result of simulation for actual land cover conditions

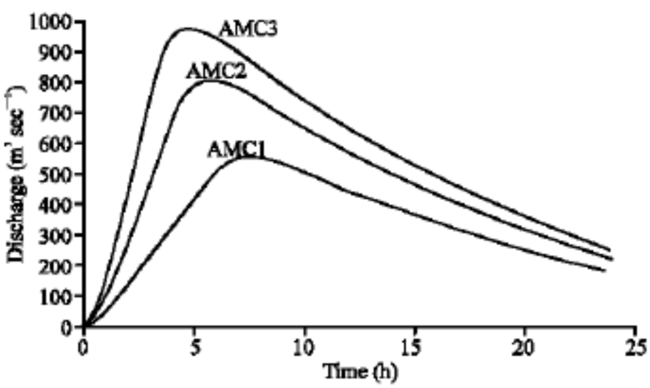

Figure 2: Results of simulation after the introduction of the hypothetical changes of land use.

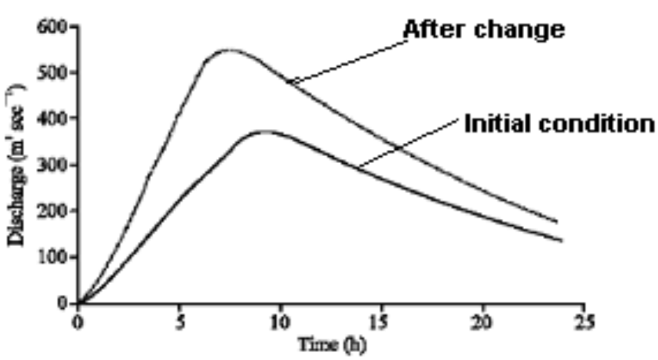

Figure 3: Results of simulation for AMCI.

moisture conditions AMC I. The results of the simulation are presented in Figure 3. The upper graph shows how the basin reacts; it has a shorter lag time, a rapid and big runoff hydrograph peak. The peak of the systems function transforming the rainfall into runoff hydrograph should increase with the growing impermeable area due to the reduced storage attenuation effect. Using the model and information on the planned future activities in the catchment it is possible to simulate the evolution of runoff for the future conditions of land use.

Conclusions

In the present study the methodology for the determination of the runoff hydrograph for the Seybousse maritime watershed using an integrated approach of remote sensing, SCS method and a physically based hydrological mode has been described. The specification of different types of land use is accomplished using SPOT-thematic mapper satellite data. Results of the application are presented, one of which is the fact that the proposed approach is able to quantify the expected changes of runoff conditions. The changes in flood peaks for different antecedent soil moisture conditions are presented. In both cases the flood produced by hypothetical land-use data is higher and tends to be faster than the flood produced by initial land-use data. This condition is expected in urbanizing catchments where a combination of an introduction of impervious areas and a modification of natural courses increases the volume of runoff and decreases the travel time of floods. In this case the increase in runoff is most likely caused by changing cultivated fields and forest areas into building plots. These changes act as a detention storage reducing the flood peak. When cultivated fields and forest areas are replaced by building plots which drain faster, an increase in flood peak is bound to occur. In the present study the increase in runoff peaks are mainly attributed to the changes in land use. Potential use of the information obtained from satellite imagery for the classification of land use represents a further advantage of this approach. This approach may be applied in other Algerian watersheds for planning conservation measures and developing effective management scenarios.

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