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Simulation the Impact of Land-Use Changes on Runoff Hydrographs Through Remote Sensing

[1]Rachid Mansouri and [2]Mazouz Kherouf Uwe Tröger
[1]LGCH Guelma, Université de Guelma, B.P 401 Guelma 24000, Algeria
[2]Department of Hydrogeology, Faculty of Civil Engineering and Geosciences, TU-Berlin, Germany

Abstract: The increase in population density and building density exert the most obvious influence on hydrological processes in an urban area. Modification of the land surface during urbanisation alters the stormwater runoff characteristics. The major modification which alters the runoff process is the impervious surfaces of the catchment such as roofs, side walks, roadways and parking lots, which were previously pervious. Within the framework, 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. Future changes in land use can also be incorporated in the model once digital database is available and the change in runoff production can be found out. Thus land-use planning and management can be done efficiently. The relationships developed between changes in runoff with respect to a change in CN are very useful to quantify the effect of land-use change. The change in peak runoff values can be estimated for a basin having known changes in land-use for known rainfall. The study clearly demonstrated 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

Urbanization of a watershed has a profound impact on runoff hydrographs. Increased impervious surfaces are a common cause of increased peak-runoff volumes. Examples of impervious surfaces include paved streets parking lots and Roofs. Artificial channels, curbs, gutters and storm sewers increase the magnitude of flood peaks by creating smoother conveyance and decreased storage in the channel and surrounding drainage area. A combination of increased peak-runoff volumes, decreased durations and hydraulic efficiency results in more “erosive work” or hydraulic force acting on a stream channel. On the other hand, when storm flows are captured in detention facilities and gradually released, storm-flow duration increases and peak flow decreases from that of developed conditions. Under this combined effect of all these actions some catchments saw their response time divided by a factor going from five to fifteen. Consequently, a multiplication of the specific discharge peak by a factor going of five to fifty (Desbordes, 1989; Mansouri, 2004) is done. This reality is due, in urban areas, to the replacement of a natural hydrographic network using sinuous routes, not very sloping and to an overdesized urban stormwater drainage system which is equipped with a comfortable slope to decrease its diameter and thus its cost (Chocat, 1997). Thus the drainage network causes a reduction in the flow way towards the catchment outlet. The assesment of surface runoff has always been one of the major concerns of the hydrologists. The appropriate management of surface runoff has significant economic and environmental repercussions. The success of structural measures implemented to mitigate the adverse impacts of urbanization primarily depend on the accurate prediction of changes to the surface runoff hydrograph.

In many studies land-use impacts have been studied using land-use scenarios with the aim of forecasting the changes in hydrological processes in future based on some assumptions of the future state of land use. Empirical flood formulae are useful for making quick estimates of peak flow when there is very little other information available. Generally these equations are restricted in application to the size range of the basin and the climatic/hydrologic region of the world in which they were developed. Most of the empirical flood formulae

Corresponding Author: Rachid Mansouri, LGCH Guelma, Université de Guelma, B.P 401 Guelma 24000, Algeria

relate peak discharge to the drainage area of the basin. Conventional models for the prediction of river discharge require considerable hydrological and meteorological data. A collection of these data is expensive, time consuming and a difficult process. In Algeria, the availability of accurate information on runoff is scarcely available in few selected sites. However, the quickening of the watershed management programme for the conservation and development of natural resources management has necessitated runoff information. Advances in computational power and the growing availability of spatial data have made it possible to accurately predict the runoff.

Satellite remote sensing can be used to determine changes in land-cover on a seasonal and long-term basis. In most parts of the world land-use data can be obtained from Landsat images made by various Landsat missions since 1972. Other satellite missions for scanning the earth's surface which also provide land use data, include SPOT, ADEOS, ERS , ALSAT1 etc. Landsat data have been used to improve empirical regression equations of various runoff characteristics. 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. 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. 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 (Scultz, 2000). In Algeria the need of accurate information on basin runoff has been felt for the past two decades along with the acceleration of watershed management for the conservation and development of soil and water resources. Advances in computational power and the growing availability of spatial data have made it possible to accurately describe watershed characteristics for the modeling of watershed hydrology. Recent studies (Schumann *et al*., 2000; Saxena *et al*., 2000; Shrestha, 2003) revealed that Remote Sensing (RS) techniques are of great use in the characterization and prioritization of watershed areas. Land use/land cover is the category in which RS has made its largest impact and comes closest to maximizing the capability of this technology. Michelini (1995) developed a model that would generate a unit hydrograph for a watershed automatically by processing a Digital Elevation Model (DEM) file. The motivation behind his research implied a reduction of the human subjectivity involved in developing unit hydrographs and the resulting direct runoff hydrographs. In order to compute the time of concentration values in the watershed he used the SCS method. Khan (2002) began the transition from a lumped to a distributed model. To this end, Khan made the process of curve number generation spatially distributed by developing a program that computed curve number values for each cell within the raster file representing the watershed area, using soil and land coverage raster files as inputs. He implemented the SCS overland flow velocity equations as the method to compute the velocity values required to obtain time of concentration values for overland flow. 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.

MATERIALS AND METHODS

The SCS curve number method: The origin of the curve number methodology can be traced back to the thousands of infiltrometer tests carried out by SCS in the late 1930s and early 1940s (Ponce *et al*., 1996). The intent was to develop basic data to evaluate the effects of watershed treatment and soil conservation measures on the rainfall-runoff process. The Soil Conservation Service (SCS) model developed by the United States Department of Agriculture (USDA) computes direct runoff through an empirical equation that requires the rainfall and a watershed coefficient as inputs. The watershed coefficient is called the Curve Number (CN) which represents the runoff potential of the land cover soil complex. This model involves the relationship between land cover, hydrologic soil class and curve number. In the past 30 years, the SCS method has been used by a few researchers because it gives consistently usable results (Sharma *et al*., 2001; Chandramohan and Durbude, 2001; Sharma and Kumar, 2002) for runoff estimation. In the present investigation an attempt is made to establish the SCS Curve Number from the Algerian remote sensing digital database for seybousse martime 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 principle behind this methodology (Fig. 1) is that the depth of excess precipitation is always less than or equal to the depth of precipitation, likewise after runoff begins, the additional depth of water retained in the watershed is less than or equal to some potential maximum retention. There is some amount of rainfall Ia for which no runoff will occur,

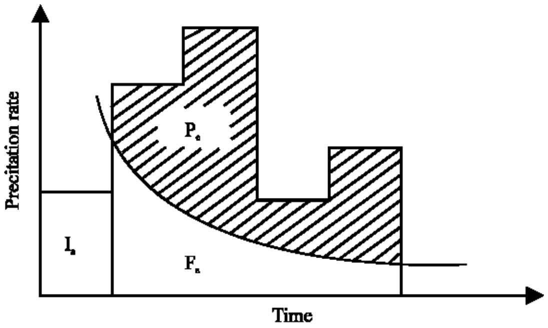

Fig. 1: Variables in the SCS method of rainfall abstraction

so the potential runoff is (P-I_a). According to the SOIL CONSERVATION SERVICE (1972) hypothesis the ratios of the two actual to the two potential quantities are equal, that is

$$\frac{F_a}{S} = \frac{P_e}{(P - I_a)} \tag{1}$$

From continuity principle

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

Where P_e = accumulated precipitation excess at time t; P = accumulated rainfall depth at time t; I_a = the initial abstraction (initial loss); F_a= continuing abstraction and S = potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation. Combining Eq. 1 and 2 yields:

$$P_e = \left((P - I_a)^2\right)/(P - I_a + S) \tag{3}$$

This is the basic equation for computing the depth of excess rainfall or direct runoff from a storm. Until the accumulated rainfall exceeds the initial abstraction, the precipitation excess and hence the runoff, will be zero. Initial abstractions are water losses (such as plant interception, infiltration and surface storage) 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 (1985) as:

$$I_a = \lambda . S \tag{4}$$

Where λ is an initial abstraction ratio. The standard assumption is that I_a = 0.2S (USDA-SCS, 1985). The "0.2" was based on watershed measurements with a large degree of variability and other researchers have reported using values ranging from 0.0 to 0.3 (USDA SCS, 1985; Ponce and Hawkins, 1996). 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. Therefore, the cumulative excess at time *t* is:

$$P_e = \frac{(P - 0.21a)^2}{P + 0.8S} \tag{5}$$

Incremental excess for a time interval is computed as the difference between the accumulated excess at the end of and beginning of the period. The maximum retention, S and watershed characteristics are related through an intermediate parameter, the curve number (commonly abbreviated CN) as:

$$S = \frac{254000 - 254CN}{CN} \tag{6}$$

CN values range from 100 (for water bodies) to approximately 30 for permeable soils with high infiltration rates. The CN for a watershed can be estimated as a function of land use, soil type and antecedent watershed moisture, using tables published by the SCS. With these tables and knowledge of the soil type and land use, the single-valued CN can be found. For a watershed that consists of several soil types and land uses, a composite CN is calculated as:

$$CN_{composite} = \frac{\Sigma A_i Cn_i}{\Sigma A_i} \tag{7}$$

In which $CN_{composite}$ = the composite CN used for runoff volume computations ; i = an index of watershed subdivisions of uniform land use and soil type; CN_i = the CN for subdivision i; and A_i = the drainage area of subdivision i.

Publications from the Soil Conservation Service (1971) provide further background and details on the use of the CN model. The curve number can be adjusted to estimate less runoff under dry conditions and more runoff under wet conditions (USDA-SCS, 1985). NEH-4 provides guidance for this adjustment based on the amount of rainfall over the previous five days. The appropriateness of this guidance is likely to depend on the location and size of the watershed (Ponce and Hawkins, 1996). The combination of a hydrologic soil group and a land use is a hydrologic soil-cover complex. To each combination is assigned a CN which is an index to its runoff potential on soil that is not frozen. A list of these values is published in Technical Report 55 (commonly referred to as TR-55). 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 or snowmelt. The curve is for normal antecedent moisture conditions (AMC II). For dry condition (AMC I) or wet condition (AMC III) equivalent curve numbers can be calculated as follow.

$$\mathrm{CN(I)} = \left(4.2\mathrm{CN(II)}\right)/\left(10 - 0.058\mathrm{CN(II)}\right) \tag{8.a}$$

$$\mathrm{CN(III)} = \left(23\mathrm{CN(II)}\right)/\left(10 + 0.13\mathrm{CN(II)}\right) \tag{8.b}$$

The SCS curve number has been applied in many countries throughout the world. Therefore, its expression in SI units is necessary. In SI units Eq. 5 converts to:

$$P_e = \frac{\left[\left(P/25{,}4\right) - \left(200/C_N\right) + 2\right]^2}{\left(P/25{,}4\right) + \left(800/C_N\right) - 8} * 25{,}4 \quad \text{in mm} \tag{9}$$

Physical model: A watershed is the area covering all the land that contributes runoff water to a common point. It is a natural physiographic or ecological unit composed of interrelated parts and functions. 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. 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 modeling. The Model developed by Wittenberg (1974) provided us a primary source of inspiration. This model is composed by two parallel cascades of linear reservoirs (Fig. 2).

As we can note the parallel cascade model is characterized by the five following 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
F	:	Dividing factor between the cascades.

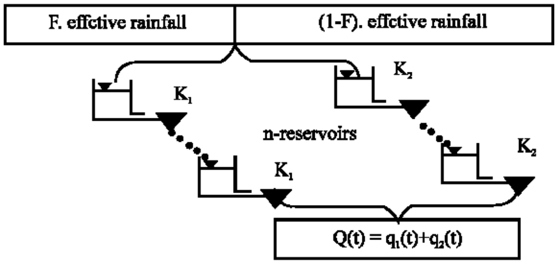

Fig. 2: Parallel cascades of linear reservoirs

The runoff process in mixed catchment is divided into the discharge from impervious surface and the discharge from pervious areas. 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:

$$\begin{aligned} u(t) = {} & F\left\{\frac{1}{k1\left(n1-1\right)}\left(\frac{t}{k1}\right)^{\left(n1^{-1}\right)} * e^{-t/k1}\right\} \\ & + (1-F)\left\{\frac{1}{k2\left(n2-1\right)}\left(\frac{t}{k2}\right)^{\left(n2^{-1}\right)} * e^{-t/k2}\right\} \end{aligned} \tag{10}$$

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 the DVWK (1980), the two parameters k_1, k_2 are determined by using the Eq. (11) and (12),

$$k1 = 0.731.\left(1F/\sqrt{I}\right)^{0.281} \tag{11}$$

$$k_2 = 3.04 * k_1^{1.29} \tag{12}$$

Where: l_F : the longest flow path length ; I : the slope

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

$$F = 2.41.\left(l_F/\sqrt{I}\right)^{-0.574} \tag{13}$$

RESULTS AND DISCUSSION

The study area: The Seybousse catchment located in eastern Algeria has undergone rapid urbanization and tremendous economic growth during the past few years. Most of the economic development activities are focused in and around the city of Annaba. These changes can transform the subcatchment " bassin Seybousse maritime" from a subsistence agrarian economy into a rapidly industrialized region. The growing urbanization in the outer periphery of Annaba city has created pressure for the changes in the land use pattern. Infrastructure development (e.g., road networks, electricity) has further enhanced the land use change process in the area. 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 between 7,701366 to 7,805208 E longitude and 36,468339 to 36,883900 N latitude with an elevation ranging from 10-750 m above MSL (Mean Sea Level) and extends over a total area of 246.421 km$^{2.}$

Classification of the satellite image: In the SCS method of runoff estimation, the effects of the surface conditions of a watershed are evaluated by means of land-use classes. Land use is the watershed cover and it includes every kind of vegetation, litter and mulch, fallow (bare soil), as well as nonagricultural uses such as water surfaces and impervious surfaces, such as roads, roofs, etc. The classes consist of use combinations actually to be found on watersheds. Two methods of classification are commonly used: Unsupervised and Supervised. In this study we limit ourselves, 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. The strategy is simple: the specialist must recognize conventional classes (real and familiar) or meaningful (but somewhat artificial) classes in a scene from prior knowledge, such as, personal experience with the region, by experience with thematic maps, or by on-site visits. This familiarity allows the specialist to choose and set up discrete classes (thus supervising the selection) and then, assigns to them category names. The specialists also locate training sites on the image to identify the classes. Training sites are areas representing each known land cover category that appear fairly homogeneous on the image (as determined by similarity in tone or color within shapes delineating the category). Specialists locate and circumscribe them with polygonal boundaries drawn (using the computer mouse) on the image display. For each class thus outlined, mean values and variances of the DNS for each band used to classify them are calculated from all the pixels enclosed in the site. More than one polygon can be established for any class. When DNS are plotted as a function of the band sequence (increasing with wavelength), the result is a spectral signature or spectral response curve for that class. In reality the spectral signature is for all of the materials within the site that interact with the incoming radiation.

The multispectral image used in this study is from sensors HRV 2 in spectral mode XS of the satellite SPOT 4. 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 20×20 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 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. The soil map of a 1:25,000 scale was traced, scanned and exported to ENVI. Image to image registration was performed using the registered topographic maps. The scanned map was loaded in ARC/INFO and boundaries of different soil textures were digitized carefully and the polygons representing various soils were assigned and flood filled with different colors for identification. 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%) C and (13.6%) group D 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.

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

Land use	Surface [km^2]	% 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	AMCIII
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
Pe	7.8 mm	24.0 mm	41.9 mm

Determination of the input parameters: The individual CNs were found verifying the hydrological soil group by overlaying the soil and land-use/land-cover map. 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 Eq. 9 and the value of the effective rainfall P_e is obtained. The results are summarized in Table 2.

The Tc 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 Tc, one of which is the Lag Method. The SCS lag equation is an empirical approach developed by the SCS, which estimates lag time directly. The SCS lag equation is given as:

$$T_{lag} = \frac{2.587.L^{0.8}.\left(\frac{1000}{CN}-9\right)^{0.7}}{1900.H^{0.5}} \qquad (14)$$

Where: T_{lag}= Lag time [hr]; L= Hydraulic watershed length [m]; CN= Hydrologic area-weighted curve number [-]; H= Average watershed land slope [-]

T_{lag} = 0.6 . Tc, Where: T_c= time concentration [hr]

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 direction, using the following relation:

$$\text{Slope} = ((\text{HYP}(dx,dy)) / 29.5)*100 \qquad (15)$$

and masking the output map so that areas out of the catchment are eliminated. Secondly, a histogram of the slope map is created. Finally, the average slope is calculated via the aggregate operation using the average function.

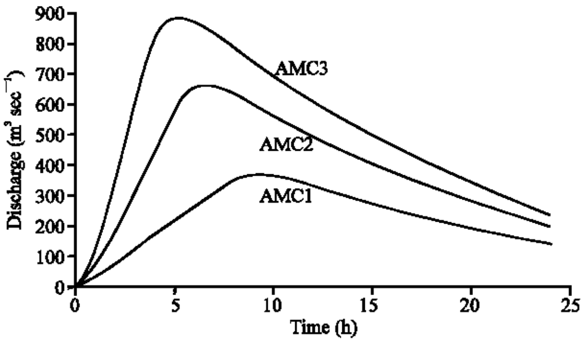

Fig. 3: Result of simulation for actual land cover conditions

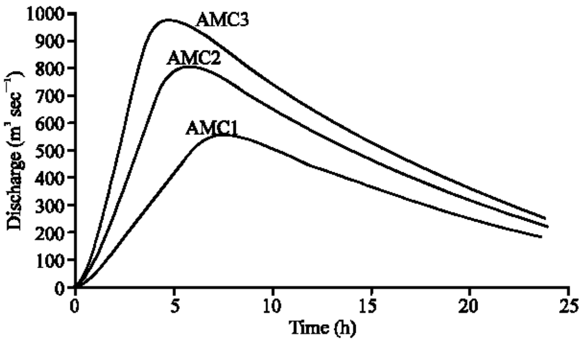

Fig. 4: Results of simulation after the introduction of the hypothetical changes of land use

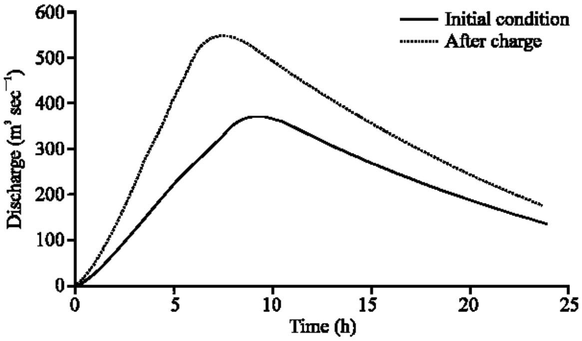

Fig. 5a: Results of simulation for AMCI

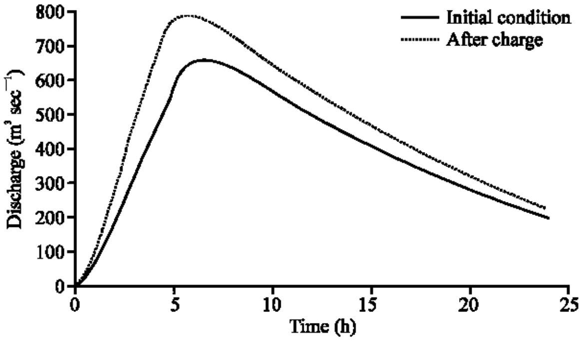

Fig. 5b: Results of simulation for AMCII

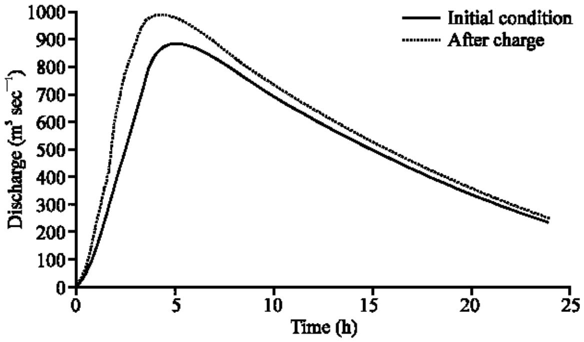

Fig. 5c: Results of simulation for AMCIII

Application: In this framework the main object is to study what effect the design flood produced by the 100 years, 24 h rainfall will have in bulk land use changes. In a first stage the method was applied for the actual land cover conditions Fig. 3, then after the introduction of the hypothetical changes of land use Fig. 4 and this for the three initial cases of initial moisture conditions AMC I, AMC II, 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. All that for the three conditions quoted above. The results of the simulation are presented in Fig. 5 a, b and c. 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 variation in percentage increase in flood peaks for different antecedent soil moisture is taken into consideration in modeling the runoff. The changes in flood peaks for different antecedent soil moisture conditions are presented in Figures. 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. Although such changes are limited and scattered in the whole basin the use of a distributed model with high-resolution land-use data enabled their effect to be simulated effectively. 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. With the help of the presented integrated approach it is possible to make management plans for the use and development of a watershed. Although the Curve Number method is an empirical approach to determine the runoff depth from the watershed, it can be helpful for estimating the effective rainfall for places which do not have runoff records.

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