

SARA – An enhanced curve number-based tool for estimating direct runoff

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ABSTRACT

This paper introduces the Spatial Analysis of surface Runoff in ArcGis (SARA v1.0) interface to estimate curve number and runoff volume for hydrologic evaluations. This version runs in a vector platform as with other extensions of ArcGIS, introducing changes to the original Natural Resources Conservation Services-Curve Number method, and allowing adaptation to local conditions. The programming syntax was developed in Visual Basic 6.0 as an ActiveX Dynamic Link Library (DLL) to interact with ArcMap, and it is released as Free and Open Source Software (FOSS) that can be modified or upgraded to other programming languages.

Key words | antecedent moisture condition, curve number, GIS, open source, runoff

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INTRODUCTION

Since Geographic Information Systems (GIS) appeared in the early 1960s, many hydrologic and environmental engineering GIS applications have been developed. With advances in computer technology and communication systems, new tools are continuously developed and offered either commercially or free for many purposes and end users, beyond their computer skills, budget or technology accessibility. This situation allows a rich-information environment that enables the enhancement and development of new methodologies and approaches to solving hydrologic and environmental issues (Gourbesville 2009). Furthermore, this advance improves the forecasting capabilities for hydrologic process by modeling possible scenarios and future conditions that are required for the planning, design and management strategies for water resources and their environments (Chau *et al.* 2005; Cheng *et al.* 2008).

As part of this approach, the estimation of hydrologic budgets at watershed level, through the balance of their components (runoff, evaporation, transpiration, evapotranspiration, interception, and groundwater), is then essential to evaluate impacts on the quality and availability of water supplies due to land cover changes, groundwater extraction or alteration to the natural flow regimes. Computations

based on data series recorded locally at the river basin are becoming an essential tool for these purposes.

Hydrological models such as AGNPS (Agricultural Non-point Source Pollution Model), SWAT (Soil and Water Assessment Tool) and LTHIA (Long-Term Hydrologic Impact Assessment), developed by Young *et al.* (1989), Arnold *et al.* (1998), and Lim *et al.* (2001) respectively, have been integrated into GIS platforms, making possible the calculation of watershed parameters such as runoff (mostly based on the Natural Resources Conservation Services-Curve Number; NRCS-CN, formerly Soil Conservation Services-Curve Number; SCS-CN), and improve the estimate's accuracy using spatially distributed hydrological modeling.

The NRCS-CN method, widely used to estimate direct runoff, water recharge, stream flow, infiltration and soil moisture content from rainfall data (Mack 1995), is popular among hydrology software developers because of its simplicity and accuracy (Shadeed & Almasri 2010), and subsequently was selected for the purposes of the present study. This method is described in detail in the National Engineering Handbook Section 4: Hydrology (NEH-4) from the United States Department of Agriculture (USDA 1986, 2004). Its applications, including hydraulic engineering and environmental impact assessments, have been discussed

in recent hydrologic literature (Mishra & Singh 2004a, b, 2006; Mishra *et al.* 2005; Huang *et al.* 2006, 2007; Kim & Lee 2008; Sahu *et al.* 2010; Cao *et al.* 2011).

Considering this factor, new interfaces using Visual Basic have been developed within the ArcGIS platform (a vector-structured GIS system from the Environmental Systems Research Institute; ESRI) that integrates the NRCS-CN or similar methods for different applications in hydrological models. These tools include ArcCN-Runoff (Zhan & Huang 2004), ArcGIS-SWAT (Olivera *et al.* 2006), the Automated Geospatial Watershed Assessment tool (AGWA) developed by Miller *et al.* (2007), the NRCS GeoHydro 9x (Merkel *et al.* 2008) and the ISRE-CN (Interface for Surface Runoff Estimation using Curve Number techniques) by Patil *et al.* (2008). Regardless of the capabilities or advantages of any of these tools, they limit the user's ability to modify or adapt the NRCS-CN method because, with the exception of ArcCN-Runoff, none of these methods allows modifications on the source code, and therefore restrains its application when conditions are not ideal for the model's assumptions.

Recent findings indicate that the NRCS-CN method in its classic form is not always appropriate for every hydrological system. Before runoff starts, part of the rainfall is evaporated, retained in surface, intercepted by vegetation or infiltrated, and this event is known as the initial abstraction (I_a) value, and together with rainfall data values are required parameters for runoff calculation. It is normally estimated as $I_a = 0.2S$, where S is the maximum potential of moisture retention after runoff begins (USDA 1986), but the relationship is not always linear as stated by Melesse & Shih (2002). Moreover, Hawkins *et al.* (2002), Baltas *et al.* (2007), Singh *et al.* (2008) and Patil *et al.* (2008), among others, suggest values from 0.05 to 0.3 to relate both parameters, depending on the extent and soil conditions of the study area. Most of the software developments for enhancing runoff estimates based on NRCS-CN set a fixed value $S = 0.2$ (Babu & Mishra 2012), while only CN-Idris, a raster-based tool that also outputs runoff estimates based on the NRCS-CN method, includes 0.05 as a second option for the initial abstraction value (Hernández-Guzmán *et al.* 2011).

To resolve this shortcoming, we introduce the Spatial Analysis of surface Runoff in ArcGIS (SARA v1.0), an interface developed in Visual Basic 6.0 as an ActiveX Dynamic

Link Library (DLL) project, which is a format that makes it easily portable among ArcMap sessions. This interface allows several changes to the default input data to adapt the model to local conditions, resulting in one of the highlights of this approach. It also represents an attempt to close the gap between vector- and raster-oriented systems, and provides an enhanced version of CN-Idris for the ArcGIS platform.

NRCS-CN METHODS USED IN THE INTERFACE

Although the NRCS-CN method is accepted globally and used regularly for watershed runoff modeling, it is not a standard model, in that some variations have been reported (Mishra *et al.* 2003). As many changes have been undertaken to include different antecedent moisture condition (AMCs), land use conditions, and initial abstraction (I_a) values, SARA v1.0 allows the users to select among different options to fit their own interests. The original model used to develop the interface and its modifications are briefly described below.

The basic NRCS-CN hydrologic model

The standard SCS-CN model (USDA 1986) is a simple method, widely recognized and commonly used to estimate the total runoff or depth of runoff (Q), over an entire basin in a 24-hour storm event. Some properties of this method make it attractive to develop tools for its application. Ponce & Hawkins (1996) suggest that runoff curve method is simple, predictable and stable, among other characteristics, but also describe some disadvantages for this method. We considered all these factors previously when developing the tool, having in mind that it is regularly applied for hydrology engineering and environmental impact assessment purposes, but also with regard to the fact that the original method is the basis for more complex hydrologic models.

The model balances precipitation (P), the initial abstraction (I_a), and the potential water retention after runoff begins (S). The empirical model that combines these parameters (originally measured in inches, but here in mm) is as follows:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad P > I_a \quad (1)$$

Based on several studies, the NRCS determined that there was a linear relationship between I_a and S , resulting in empirical solution of $I_a = 0.2S$ (USDA 1986; Melesse & Shih 2002). Simplifying the above equation, runoff can be estimated as follows:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (2)$$

The S parameter value depends on the soil capacity for water runoff or infiltration. Therefore, it is possible to estimate the value as described below using the CN, an empirical parameter based on the hydrologic soil groups (HSG), land use, treatment and hydrologic conditions (USDA 1986; Ponce & Hawkins 1996).

$$S = \frac{25400}{CN} - 254 \quad (\text{mm}) \quad (3)$$

The CN is dimensionless ranging from 0 when $S \rightarrow \infty$, up to 100 when $S = 0$. Both conditions represent the extremes between total infiltration (runoff = 0) and totally impervious watersheds (rainfall = runoff). However, many of the computations use 30 as the lowest value, even when lower values could be detected (USDA 1986).

To estimate CN values, the NRCS has provided runoff curve number tables for different cover types (agricultural, arid and semiarid rangelands and urban areas), hydrologic conditions (poor, fair, good) and the HSG. The HSG is a standard soil classification (groups A, B, C, D) that depends on soil texture and infiltration rates. The A group includes well-drained soils with a high rate of infiltration, whereas D soils are poorly drained with a permanently high water table (USDA 1986).

Antecedent moisture condition

The NRCS introduced the AMC concept to determine soil moisture before a storm event, the condition of which could affect the calculation of runoff. There are three conditions for dry (AMC I), normal (AMC II) and saturated soils (AMC III) that are assigned as a function of the five-day antecedent rainfall. The moisture condition could

affect runoff estimates because it modifies the CN whose standard values are set to the AMC II by default. The option of selecting a soil condition is included in the interface, and users must be aware of soil conditions to select the correct AMC.

After selecting the AMC, the standard CN values are derived from the National Engineering Handbook; Section 4 (NEH-4) tables and, if necessary, converted to AMC I or AMC III using the following functions (USDA 2004):

$$CN_I = \frac{4.2CN_{II}}{10 - 0.058CN_{II}} \quad (4)$$

$$CN_{III} = \frac{23CN_{II}}{10 - 0.13CN_{II}} \quad (5)$$

Modified NRCS-CN method ($I_a/S = 0.05$)

The original NRCS-CN method assumes that the ratio $I_a/S = \lambda$ (where λ is a parameter dependent on regional climatic or geological factors), takes a value of 0.2, ranging from 0.1 to 0.3 (Patil *et al.* 2008). However, findings by Hawkins *et al.* (2002) based on a large rainfall-runoff dataset lead to conclude that λ is not constant for every storm and varies widely from 0.0005 to 0.4910 with a median of 0.0476 and a distribution skewed to the lower end of the scale. The authors concluded that $\lambda = 0.05$ is a better fit than 0.2 for the observed rainfall-runoff data and have recommended this value for the runoff calculation, using the next equation:

$$Q = \frac{(P - 0.05S_{0.05})^2}{P + 0.95S_{0.05}} \quad P > 0.05S \quad (6)$$

When the abstraction I_a is lower than $0.2S$, a more realistic value must be calculated (Lim *et al.* 2006), using the relationship between $S = 0.05$ and $S = 0.2$ defined by Hawkins *et al.* (2002):

$$S_{0.05} = 1.33S_{0.2}^{1.15} \quad (\text{in}) \quad (7)$$

When extreme precipitation events occur in a watershed, producing immediately water saturation conditions,

it is possible to introduce the zero initial abstraction ($I_a = 0$) concept, to calculate the runoff depth (Q). Also, on the hypothesis that $I_a = \lambda S$, SARA v1.0 allows the user to select different values of I_a through the *custom user* function, in contrast with most CN software developments that offer only fixed values. This option is included here, as it is also in the ISRE-CN tool developed by Patil *et al.* (2008).

SOFTWARE DESCRIPTION AND SCOPE

The models described above and their calculation (except Equation (1)) were integrated and codified in SARA v1.0. This tool is based on a previous source code following the principle of code reuse, mainly using the open source tool ArcCN-Runoff (Zhan & Huang 2004). SARA v1.0 retains the curve number reference table and the ‘Match function’ developed by those authors to search for any cover included in the land use database and to match the selection to the CN reference table.

SARA v1.0 is a DLL file that, once installed, is displayed as any other module in ArcGIS as a drop-down menu, allowing user interaction to select among the different options of I_a values or the AMC, upload the input data (Landsoil layer),

and finally configuring the output to obtain CN values and runoff depth (Q) and volume, or both (Figure 1(a)).

The functioning of this tool requires that several data sets be available in the ArcMap document (.mxd file) to select the input parameters. The ‘Landsoil layer’, that can be created using standard geoprocessing techniques (intersection), must be included with each polygon encompassing information on Land Use (Landuse field), HSG field, and Area (Area field) in square meters. This tool also requires a CN database, that can be built with reference data as those compiled in the TR-55: Urban Hydrology for Small Watersheds manual (USDA 1986) or from similar watershed models, but when possible it is desirable that CN values can be derived from local data. Data including the land use categories and CN values by HSG can be edited as a worksheet and later exported to dBase format (dbf), as required by the tool (Figure 2).

As described by Zhan & Huang (2004), it is essential to match the cover types from the land use layer with those stored in the CN reference table and it can be done retrieving the ‘Match SubClass of Land_use’ option (Figures 1(b)–1(d)). This option displays classes from the land soil layer (1b) and the CN database (1c), producing a third item (1d), after classes from previous databases are matched.

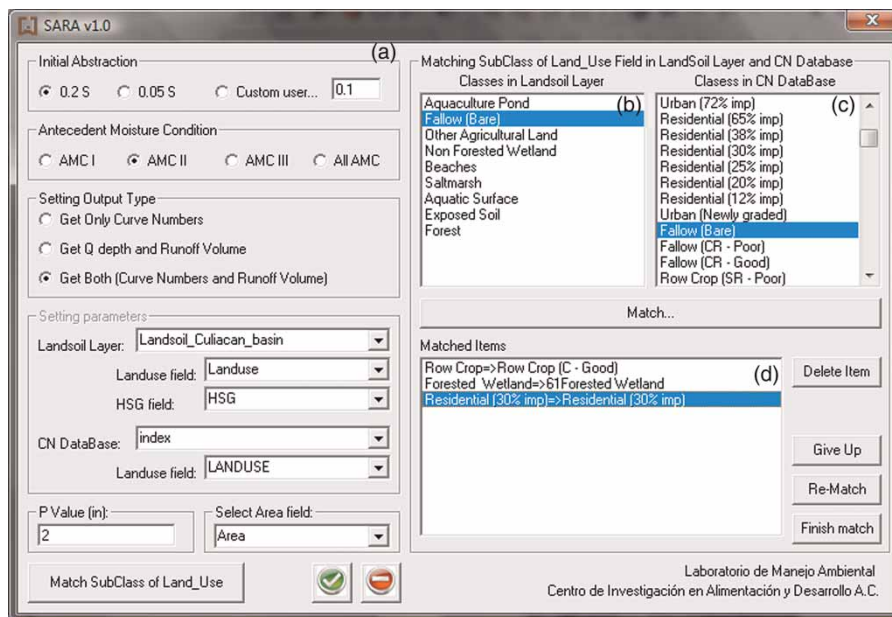
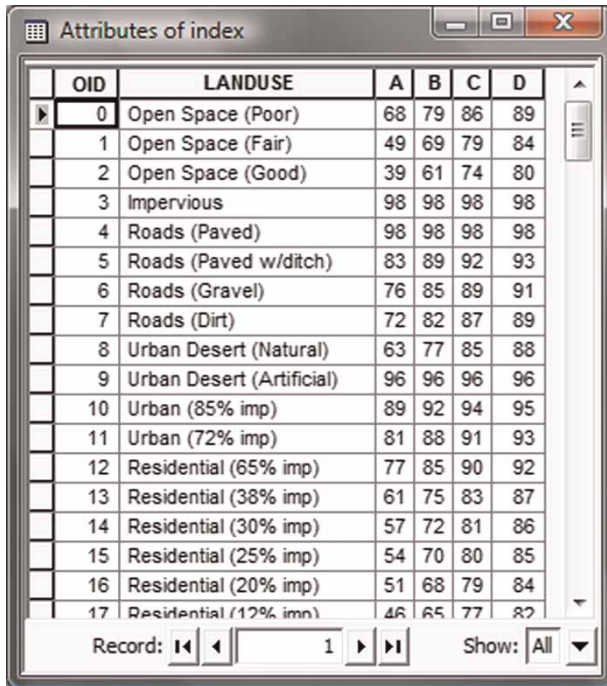


Figure 1 | Spatial Analysis of surface Runoff in ArcGis (SARA v1.0) interface to assess curve number and runoff volume with different inputs and conditions. (a) Main screen for input data and parameter selection. (b) Landsoil classes for the study area. (c) Standard curve number (CN) classes. (d) Matched land soil and CN classes.



OID	LANDUSE	A	B	C	D
0	Open Space (Poor)	68	79	86	89
1	Open Space (Fair)	49	69	79	84
2	Open Space (Good)	39	61	74	80
3	Impervious	98	98	98	98
4	Roads (Paved)	98	98	98	98
5	Roads (Paved w/ditch)	83	89	92	93
6	Roads (Gravel)	76	85	89	91
7	Roads (Dirt)	72	82	87	89
8	Urban Desert (Natural)	63	77	85	88
9	Urban Desert (Artificial)	96	96	96	96
10	Urban (85% imp)	89	92	94	95
11	Urban (72% imp)	81	88	91	93
12	Residential (65% imp)	77	85	90	92
13	Residential (38% imp)	61	75	83	87
14	Residential (30% imp)	57	72	81	86
15	Residential (25% imp)	54	70	80	85
16	Residential (20% imp)	51	68	79	84
17	Residential (12% imp)	46	65	77	82

Figure 2 | Attribute table with curve number (CN) values by land use category and hydrologic soil group (A–D).

When all required fields are filled, SARA v1.0 first assigns CN standard values to polygons derived from the Landsoil layer, taking the AMC II by default. Following this, different scenarios can be modeled, adapting them if necessary to AMC I or AMC III environments according to the procedures described by the [USDA \(2004\)](#). However, when $I_a = 0.05 * S$ is selected as the initial abstraction value, it is only possible to model with AMC II because the S value must be recalculated using the relation between $S = 0.05$ and $S = 0.2$ defined by [Hawkins et al. \(2002\)](#).

This interface was developed in a vector GIS, but a previous analogous tool for raster format was created to produce similar outputs (CN-Idris; [Hernández-Guzmán et al. 2011](#)). To make both tools comparable, SARA v1.0 follows the same logic as CN-Idris, but here, the users can perform a comprehensive analysis, storing the output scenarios in the attribute table of 'Landsoil layer' instead of in text files that require further management to make them available for the rest of the analysis. Other advantages to using this format include the preservation of detail when there is spatial variation of the soil and land use in the

basin and low computation restrictions, allowing tasks with a large number of polygons.

DISCUSSION

GIS oriented to hydrologic studies are increasing in number, complexity and scope, but some of them require very specific inputs or have limitations for users with different skills, software and hardware facilities. Additionally, the use of raster or vector formats as the best inputs is discussed by many users as to which prefer one or the other. Making some interfaces equivalent and comparable in both formats is one of the aims pursued by the authors of the present work.

Products such as ArcGIS 9x and later versions as well as many of the newest GIS software versions are integrating programming languages such as Python, which is a high level language that allows script writing but is also used to create large programs. However, previous versions and other GIS programs, such as ArcView (still in use by many users), Idrisi, Quantum GIS, Ilwis or ENVI, use other languages or even develop their own language.

In consideration of these issues, SARA v1.0 was completely programmed in Visual Basic 6 (VB6), a programming language that can create .dll and .exe files. Visual Basic is mainly used to develop Windows applications but has now been discontinued by Microsoft, even when the runtime is supported on several Windows platform. Thus, VB6 is a common language for many types of GIS software, and it was selected to write the algorithms used to calculate different scenarios of rainfall–runoff based on the NRCS-CN method, having in mind that, with some restrictions, VB6 can migrate to the upgrade version VB.NET, regarding that SARA V1.0 code is open and free.

The architecture of this tool allows improvements in the short time, implementing an extended NRCS-CN method for long-term hydrologic simulations that incorporate other water balance components such as evapotranspiration, and the correction for slopes that differ by 5%, which is a limitation implicit in the method. Also, there is the possibility to couple with newer methodologies for rainfall–runoff time series forecasting using artificial neural networks, genetic programming or similar approaches

(Chau *et al.* 2005; Wu *et al.* 2008), improving the accuracy of this tool represents a challenge for future versions.

CONCLUSIONS

SARA v1.0 extends the possibility of using the CN method in which it is possible to introduce different configurations, making possible the adaptation to local conditions. Additionally, because it is a Free and Open Source Software (FOSS), the programming time can be reduced, allowing source code reuse and opening access to potential improvements or moving to updated programming languages.

ACKNOWLEDGEMENTS

This research is supported under Consejo Nacional de Ciencia y Tecnología funding scheme (CONACYT-Mexico, I0007–2011–01), supporting the enrollment of R. Hernández to CIAD, A.C. as a researcher.

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First received 14 September 2012; accepted in revised form 17 November 2012. Available online 11 January 2013