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Integrated runoff-erosion modelling in the Brazilian Water Resources Information System (SNIRH)

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Abstract This paper presents details of how part of the Brazilian Water Resources Information System (SNIRH) was developed. The work was carried out by four research networks made up of several Brazilian universities. One of these networks was responsible for the integration of rainfall–runoff models to the SNIRH. In order to integrate the rainfall–runoff models into the SNIRH, the OpenJUMP software was used as an interface to manage the input data and the simulation results. Among the selected models, there is a distributed runoff–erosion model named Kineros with a new friendly interface, in order to provide more detailed simulations exercises, allowing users to analyse the results easily. The model can import the rainfall data from SNIRH and separately simulate the runoff and erosion processes. Finally, this new tool, which integrates different hydrological models in a single base, can support the decision-making process for water resources in Brazil.

Key words SNIRH; runoff-erosion modelling; Kineros; OpenJump

INTRODUCTION

Brazil has made several advances in the last 10 years regarding water resources planning and management. In terms of hydrological simulations, three distinct phases can be identified: development of models, integration of these models into Decision Support Systems (DSSs), and the coupling of Geographic Information Systems (GISs), as presented by Silva & Santos (2007). Nowadays, according to demands of the Brazilian Water Resources Information System, the new challenge is to consolidate all the available knowledge into a Spatial Decision Support System (SDSS).

This paper presents details as to how part of the Brazilian Water Resources Information System (SNIRH) was developed. The work was carried out by four research networks made up of a group of Brazilian universities. One of these, Network 3, was responsible for the integration of rainfall–runoff models in the SNIRH. The selected models must deal with, amongst other issues, prediction of runoff levels and sediment yields, the impacts of changes in land use, and the estimation of water availability in ungauged basins.

This paper presents the Kineros runoff-erosion model, which was integrated into the SNIRH using an Open Geographic Information System (OpenGIS). In this way, the whole SNIRH database is available for simulations and the results can, in return, feedback into the SNIRH system, if the Brazilian National Water Agency allows. The system is presented within a new user-friendly interface which displays and plots simulation results, and allows comparison between each simulation using statistical analysis.

THE UNDERLYING BASIC SOFTWARE – AN OPENGIS

It was decided to adopt a free and open source GIS platform because the Brazilian National Water Resources Policy stated that the code of this software should be accessible to anyone. In this situation, OpenGIS, i.e. an Open Source Free GIS, was selected and OpenJUMP (www.openjump.org) was chosen as the basic program, which would be integrated with the rainfall–runoff models. This OpenGIS has been developed by the Geography Department of the University of Zurich in Switzerland, and it uses the JUMP core (JUMP, 2003), which was developed by Vivid Solutions©, a Canadian company.

The OpenGIS has many advantages. One advantage is that the OpenJUMP can access maps remotely through the standard services of the Open Geospatial Consortium (www.opengeospatial.org). The SNIRH map database can be accessed through the WMS (Web Mapping Service). The second advantage is that it allows new applications (plugins) to be integrated into the system and this was how the selected models were integrated to OpenJUMP. The third advantage is that the OpenJUMP was developed in the Java language, based on concepts of Object Oriented Programming, and taking advantage of all its resources.

The design of SNIRH-rainfall–runoff model

The SNIRH-rainfall–runoff model was made up of a set of three applications: an access module to the Hydro database of the Brazilian National Water Agency (ANA, in Portuguese); rainfall–runoff models built as plugins; and a robustness analysis module. All applications of this system are based on the OpenJUMP software, since some of the applications work with spatial entities.

Database module access

The first module developed was the software to access the ANA database, in which the Web Services technology was used. This technology allows interaction between applications developed on different platforms. In addition, it is possible for newly developed applications to communicate with those that already exist without the need for major changes. Through Web Services, it is possible to get rainfall, runoff and other data. The application accesses the ANA database, returning a collection of objects with the required information, which are then available in a graphical user interface.

A friendly graphical user interface to the models

OpenGIS is used to manage input information as well as to present the resulting simulations, in order to promote an integrated view of the basin and its elements. The chosen models were the hydrological lumped models IPH2 (Tucci *et al.*, 1981), MODHAC (Viegas Filho *et al.*, 1999) and SMAP (Lopes, 1982), and the distributed models MGBH (Collischonn *et al.*, 2007) and Kineros (Woolhiser *et al.*, 1990). Once the OpenGIS is opened, the user can select the SNIRH option in the main menu bar. The user chooses the option “models” and then they can click on the model that they want to use for their study.

The integration between the OpenGIS and models was done through an interface for exchanging data, thus data stored in the GIS layers are converted into input files for a particular model. The interface is also responsible for the model execution, and again to transfer information to the GIS layers where the simulation results are presented. In this way, GIS plays an important role for the pre- and post-processing of data.

The analysis model

After model execution, the user is able to compare all of the executed simulations within the same system. Several statistical parameters are available for this and the user does not need another software program to analyse and compare the simulation results. Several statistical measures are available such as average, deviation, variance, covariance, minimum value, maximum value, autocorrelation, BIAS, MSRE, Nash Coefficient, Pearson’s Correlation, and Coefficient of Determination.

THE KINEMATIC MODEL

The soil infiltration model

The model formulation allows a physically-based approximation for the redistribution of soil water, including recovery of infiltration capacity during a hiatus, and a method that determines infiltration rates following a hiatus. The soil infiltration model describes infiltration capacity f_c as a function of infiltrated depth I and it requires four basic parameters to describe the infiltration properties of a soil: the field-effective saturated hydraulic conductivity K_s (m s^{-1}); the integral capillary drive G (m); the porosity ϕ; and the pore size distribution index λ. There is one optional parameter, C_v, which describes the random variation in space of the hydraulic properties of the soil, and another optional parameter, *ROCK*, that allows even more explicit characterization of a soil profile via the content of large rocks. Also, there is an event-dependent variable, which is the initial relative saturation of the upper soil layer, equal to θ_i/ϕ, where θ_i is the initial soil moisture content. The general model for infiltrability, f_c (m s^{-1}), as a function of infiltrated depth, I (m), is given by Parlange *et al.* (1982):

$$f_c = K_s\left[1 + \frac{\alpha}{e^{\alpha I/B} - 1}\right] \tag{1}$$

where B is $(G + h)(\theta_s - \theta_i)$, combining the effects of net capillary drive, G, surface water depth, h (m), and unit storage capacity, $\Delta\theta = (\theta_s - \theta_i)$, in which θ_s is the soil moisture content at saturation. The parameter α represents the soil type: α is near 0 for a sandy soil, in which case equation (1) approaches the Green-Ampt relation; and α is near 1 for a well-mixed loam, in which case equation (1) represents the Smith-Parlange infiltration equation. This model accounts for soil water redistribution; i.e. it considers the interval between rainfall events which consist of more than one period of runoff-producing rainfall, with an intervening period during which significant drying of the soil can occur. The redistribution/reinfiltration method used in the model is described in Smith *et al.* (1993) and Corradini *et al.* (1994).

Overland and channel flow

Overland flow can be viewed as a one-dimensional flow process in which flux is related to the unit area storage by a simple power relation:

$$Q = ah^m \tag{2}$$

where Q is discharge per unit width (m^2 s^{-1}), and h is the storage of water per unit area (m). Parameters a and m are related to slope, surface roughness, and flow regime, and are given by $a = S^{1/2}/n$ and $m = 5/3$ where S is the slope, and n is Manning's roughness coefficient for overland flow. Similar to Santos *et al.* (2003), the continuity equation for a surface plane is given as:

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q(x,t) \tag{3}$$

where t is time (s), x is the distance along the slope direction (m), and $q(x,t)$ is the lateral inflow rate (m s^{-1}). For overland flow, equation (2) is substituted into equation (3) and the resultant equation is solved using a four-point implicit finite difference method. The continuity equation for a channel with lateral inflow is given by:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_c(x,t) \tag{4}$$

where A is the cross-sectional area (m^2), Q is the channel discharge (m^3 s^{-1}), and $q_c(x,t)$ is the net lateral inflow per unit length of channel (m^2 s^{-1}). The kinematic assumption is embodied in the relationship between channel discharge and cross-sectional area, such that:

$$Q = aR^{m-1}A \tag{5}$$

where R is the hydraulic radius (m). If the Manning equation is used, $a = S^{1/2}/n$ and $m = 5/3$. The kinematic equations for channels are solved by a four-point implicit technique similar to that for overland flow surfaces.

Upland and channel erosion

The general equation used to describe the sediment dynamics at any point along a surface flow path is a mass balance equation similar to that for kinematic water flow (Bennett, 1974):

$$\frac{\partial(AC_s)}{\partial t}+\frac{\partial(QC_s)}{\partial x}-e(x,t)=q_s(x,t) \tag{6}$$

in which C_s is the sediment concentration (m^3 m^{-3}), Q is the water discharge rate (m^3 s^{-1}), A is the cross sectional area of flow (m^2), e is the rate of erosion of the soil bed (m^2 s^{-1}), and q_s is the rate of lateral sediment inflow for channels (m^2 s^{-1}). For upland surfaces, e is assumed to be composed of two major components: production of eroded soil by rainfall splash on bare soil; and hydraulic erosion (or deposition) due to the interplay between the shearing force of water on the loose soil bed and the tendency of soil particles to settle under the force of gravity. Net erosion is a sum of the splash erosion rate, e_s, and the hydraulic erosion rate, e_h:

$$e=e_s+e_h \tag{7}$$

The splash erosion rate is estimated as follows:

$$e_s=c_f e^{-c_h h}r^2 \tag{8}$$

in which r is the effective rainfall (m s^{-1}), c_f is a constant related to soil and surface properties, and $e^{-c_h h}$ is a factor representing the reduction in splash erosion caused by increasing depth of water. The parameter c_h represents the damping effectiveness of surface water, assumed to be 364.0. The hydraulic erosion rate (e_h) is estimated as being linearly dependent on the difference between the equilibrium concentration and the current sediment concentration and is given by:

$$e_h=c_g(C_m-C_s)A \tag{9}$$

in which C_m is the concentration at equilibrium transport capacity, $C_s = C_s(x,t)$ is the current local sediment concentration, and c_g is a transfer rate coefficient (s^{-1}), which is computed as:

$$c_g=C_o\frac{v_S}{h} \quad \text{if } C_s \le C_m \text{ (erosion)} \quad \text{or} \quad c_g=\frac{v_S}{h} \quad \text{if } C_s > C_m \text{ (deposition)} \tag{10}$$

where C_o is the a soil cohesion coefficient, and v_s is the particle fall velocity (m s^{-1}). The model uses the transport capacity relation of Engelund & Hansen (1967) modified to include the unit stream power threshold found to apply to shallow flow transport. Particle settling velocity is calculated by the following equation (Fair & Geyer, 1954):

$$v_s^2=\frac{4}{3}\frac{g(\rho_s-1)d}{C_D} \tag{11}$$

in which g is the gravitational acceleration (m s^{-2}), ρ_s is sediment specific gravity, equal to 2.65, d is the sediment diameter (m), and C_D is the particle drag coefficient. The drag coefficient is a function of particle Reynolds number:

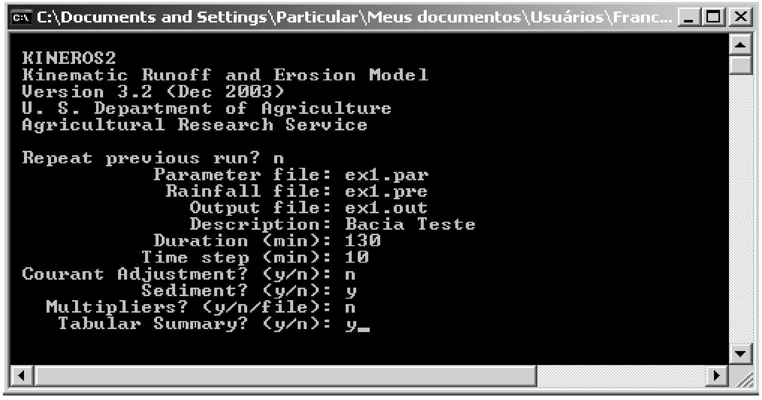
$$C_D=\frac{24}{R_n}+\frac{3}{\sqrt{R_n}}+0.34 \tag{12}$$

where R_n is the particle Reynolds number, given as $R_n = v_s d/\nu$, where ν is the kinematic viscosity of water (m^2 s^{-1}). The settling velocity of a particle is found by solving equations (11) and (12) for v_s. This series of erosion relations are applied to each of up to five particle size classes that are used to describe a soil with a range of particle sizes. Equations (6)–(12) are solved numerically at each time step used by the surface water flow equations, and for each particle size class.

The general approach to sediment transport simulation for channels is similar to that for upland areas. The major difference in the equations is that splash erosion (e_s) is neglected in channel flow, and the term q_s becomes important in representing lateral inflow.

APPLICATION OF THE KINEROS MODEL THROUGH THE SNIRH SYSTEM

An application of the runoff-erosion Kineros model is presented below. The other hydrological models, described above, have the same relation with the graphical interface. The runoff-erosion Kineros model has its source code in FORTRAN. This source code was modified so that the input information is automatically obtained from the SNIRH system (Fig. 1).



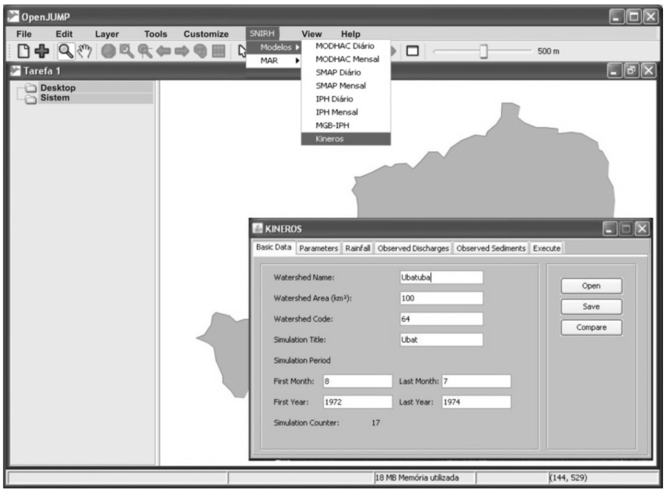
```
KINEROS2
Kinematic Runoff and Erosion Model
Version 3.2 (Dec 2003)
U. S. Department of Agriculture
Agricultural Research Service

Repeat previous run? n
           Parameter file: ex1.par
            Rainfall file: ex1.pre
              Output file: ex1.out
              Description: Bacia Teste
          Duration (min): 130
         Time step (min): 10
Courant Adjustment? (y/n): n
         Sediment? (y/n): y
  Multipliers? (y/n/file): n
   Tabular Summary? (y/n): y_
```

Fig. **1** Graphical interface model Kineros in MS-DOS.

After the source code of the Kineros had been modified, interfaces were developed for: data access and management; writing of input files; model running; and results analysis. The Graphical User Interfaces (GUIs) developed are described below.

STARTING THE KINEROS_SNIRH MODEL

Once the OpenGIS is opened, a plugin will appear on the menu on the main program named SNIRH. Clicking on the icon, the user chooses the option "models" and then can click on the model that they want to use for the study (Fig. 2). The "Basic data" function is used to open or save the basic information of the basin (name, area code, and simulation title), and the chosen period for the simulation (start and end months, initial and final years). This option stores all the information, thus it avoids the issue of having to manually load the data each time the program is restarted. For each simulation carried out, a simulation counter is updated. The Ubatuba River basin, in southeastern Brazil, is shown here as an example (Fig. 3).



Watershed Name: Ubatuba
Watershed Area (km²): 100
Watershed Code: 64
Simulation Title: Ubat
Simulation Period
First Month: 8 Last Month: 7
First Year: 1972 Last Year: 1974
Simulation Counter: 17

Fig. **2** Graphical user interface: OpenSIG and Kineros model (Step 1).

Global

Clen	Unit	Diams 0	Diams 1	D
8000.0	METRIC	.005	.05	.2

Planes

ID	UP	LEN(m)	WID(m)
1		1104.35	4600

Channels

ID	UP	LAT	LEN(m)
3		1,2	4600.0

(a)

Ubatuba

X: null

Y: null

N: 730

Time (min)	DEPTH (mm)
1440	0.0
2880	0.0
4320	0.0
5760	9.1
7200	44.1
8640	58.7
10080	68.7

(b)

Post Name	Code	Latitude (Km)	Longitude
Destilaria Bom Jesus	39220000	-8.25	-35.00

Elapsed Time (min)	Observed Discharge (m³/s)
0	0.00
1440	0.00
2880	0.00
4320	0.00
5760	0.00
7200	4.56

(c)

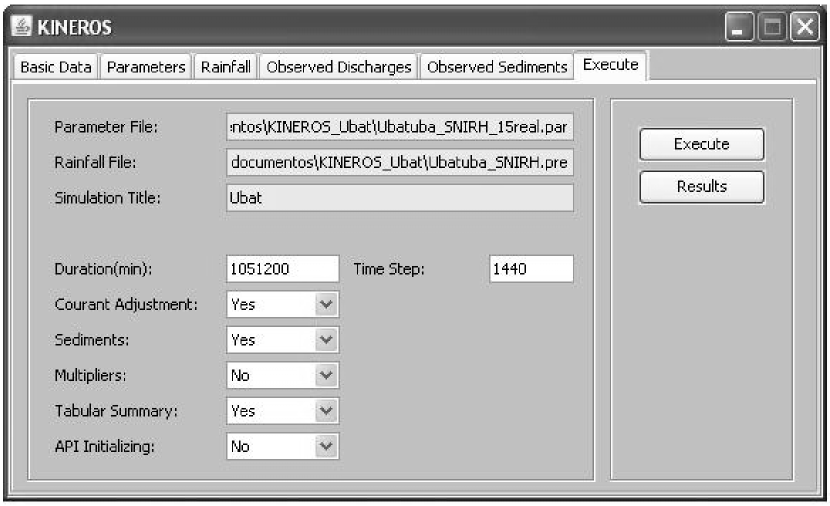
Post Name	Code	Latitude (Km)	Longitude
Destilaria Bom Jesus	39220000	-8.25	-35.00

Elapsed Time (min)	Observed Sediment (kg/s)
0	0.00
1440	0.00
2880	0.00
4320	0.00
5760	52.82
7200	51.06

(d)

Fig. **3** Graphical user interfaces of the model input data: (a) input parameter data (step 2), (b) rainfall data (step 3), (c) observed runoff (step 4), and (d) observed sediment yield (step 5).

Once the input files are created, the model is run (Fig. 4). By clicking on "Execute", the precipitation files and parameters are loaded automatically and all that is required is to fill the remaining fields on the screen. After the simulation is processed, observed and computed runoff and sediment yield values are available within "Results".



Parameter File: ntos\KINEROS_Ubat\Ubatuba_SNIRH_15real.par

Rainfall File: documentos\KINEROS_Ubat\Ubatuba_SNIRH.pre

Simulation Title: Ubat

Duration(min): 1051200

Time Step: 1440

Courant Adjustment: Yes

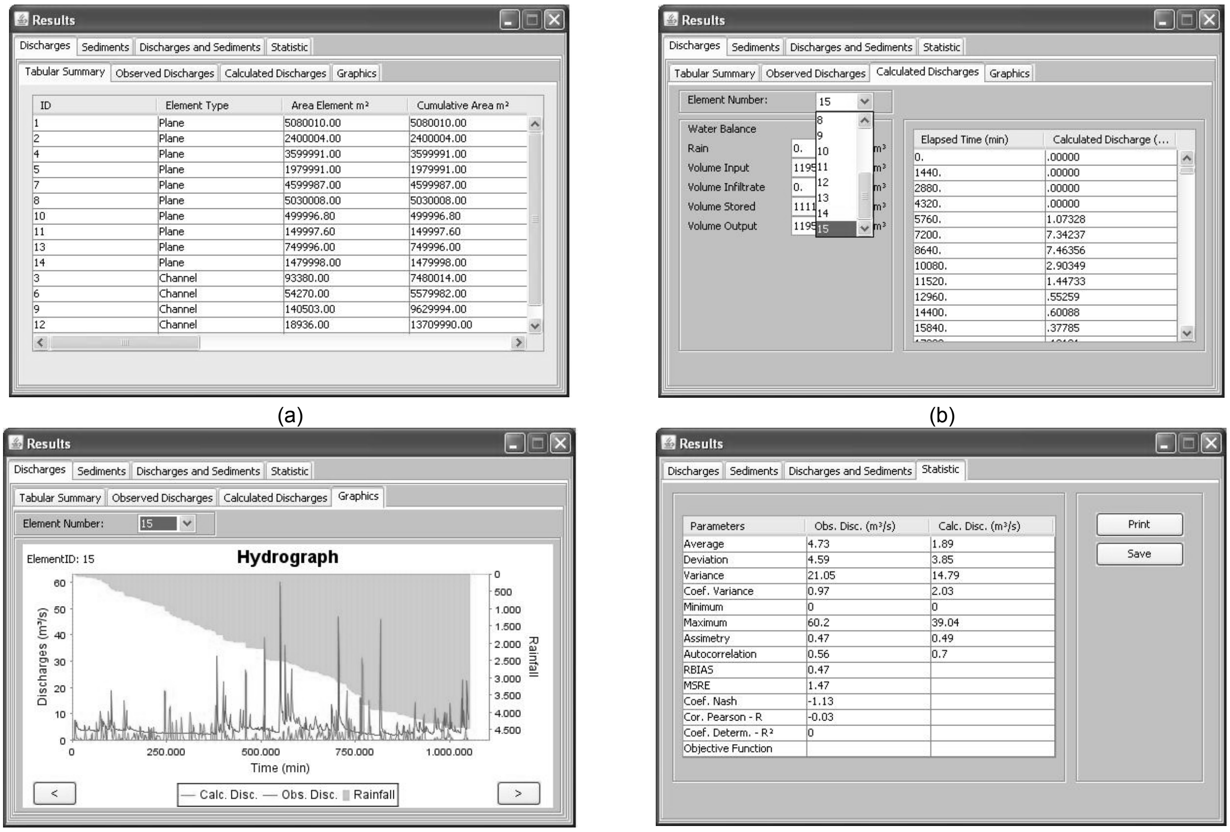
Sediments: Yes

Multipliers: No

Tabular Summary: Yes

API Initializing: No

Fig. 4 Window of the model running process (step 6).



ID	Element Type	Area Element m²	Cumulative Area m²
1	Plane	5080010.00	5080010.00
2	Plane	2400004.00	2400004.00
4	Plane	3599991.00	3599991.00
5	Plane	1979991.00	1979991.00
7	Plane	4599987.00	4599987.00
8	Plane	5030008.00	5030008.00
10	Plane	499996.80	499996.80
11	Plane	149997.60	149997.60
13	Plane	749996.00	749996.00
14	Plane	1479998.00	1479998.00
3	Channel	93380.00	7480014.00
6	Channel	54270.00	5579982.00
9	Channel	140503.00	9629994.00
12	Channel	18936.00	13709990.00

(a)

Element Number: 15

Water Balance
Rain 0. m³
Volume Input 1195 m³
Volume Infiltrate 0. m³
Volume Stored 1111 m³
Volume Output 1195 m³

Elapsed Time (min)	Calculated Discharge (...
0.	.00000
1440.	.00000
2880.	.00000
4320.	.00000
5760.	1.07328
7200.	7.34237
8640.	7.46356
10080.	2.90349
11520.	1.44733
12960.	.55259
14400.	.60088
15840.	.37785

(b)

Element Number: 15

(c)

Parameters	Obs. Disc. (m³/s)	Calc. Disc. (m³/s)
Average	4.73	1.89
Deviation	4.59	3.85
Variance	21.05	14.79
Coef. Variance	0.97	2.03
Minimum	0	0
Maximum	60.2	39.04
Assimetry	0.47	0.49
Autocorrelation	0.56	0.7
RBIAS	0.47	
MSRE	1.47	
Coef. Nash	-1.13	
Cor. Pearson - R	-0.03	
Coef. Determ. - R²	0	
Objective Function		

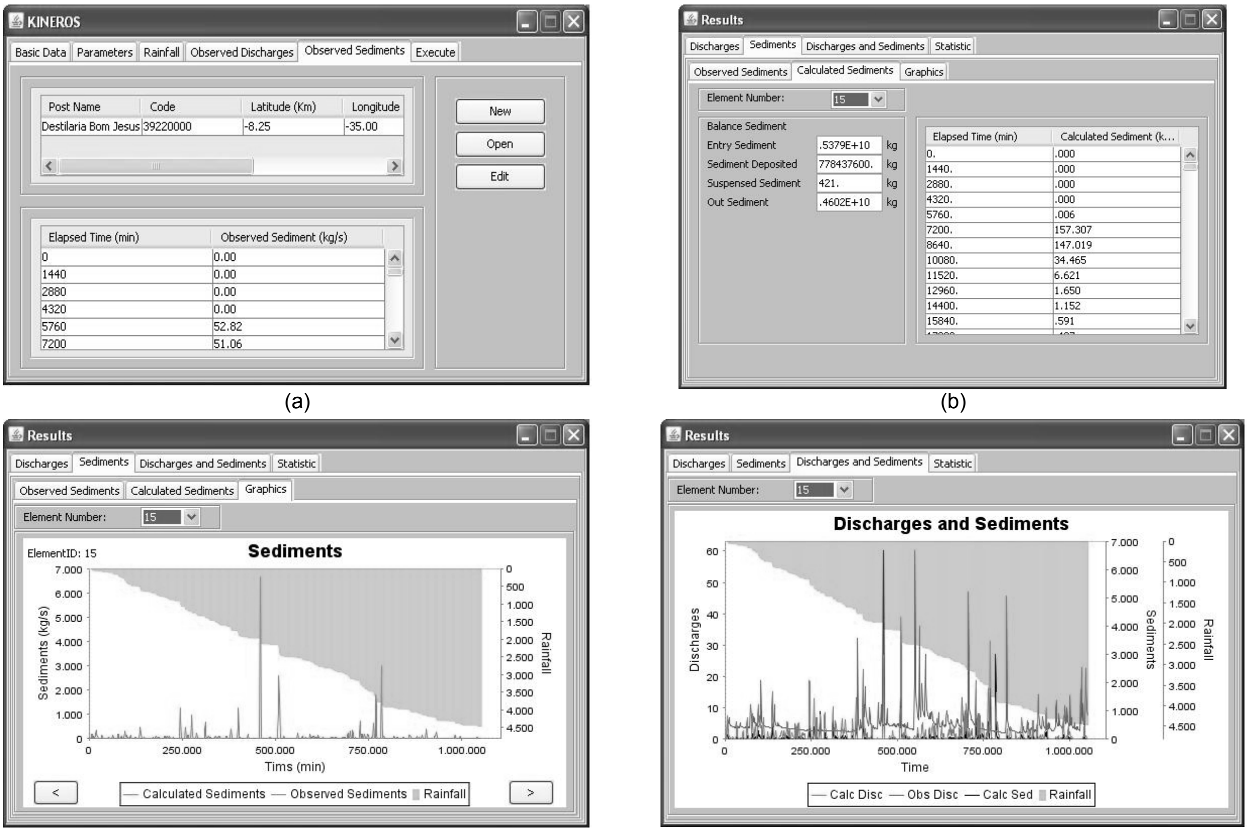
(d)

Fig. **5** Windows of the model execution process: (a) characteristic for each discretized element (step 7), (b) computed runoff (step 8), (c) observed hyetograph and computed and observed hydrographs (step 9), and (d) simulation statistics (step 10).

Figures 5 and 6 show the results of the simulation process for the runoff and sediment yield, respectively. Figure 6(b) shows the sediment budget (input, output and deposition) for each element. The user could analyse the results of each element separately, in which case they could select the element number for analysis of the respective results. Once an element is chosen, the sediment budget values are loaded and it is possible to determine the total sediment yield at the sub-basin outlet. A careful analysis of the hydrographs and sedigraphs allows the user to estimate runoff generation and sediment yield in a particular section of the basin and to understand better the response of the basin to changes in basin conditions.

CONCLUSIONS

The integration of a runoff-erosion model within SNIRH allowed the development team to create an open source and free software that can be run on any operational system that has a Java Virtual Machine, e.g. Windows®, Linux, etc. The way that the hydrological models were integrated into the OpenJUMP software means that it was not necessary to implement the hydrological models in Java language. Nevertheless, the use of an OpenGIS avoids the issue that new GIS functions need to be implemented. With respect to the Kineros model, a new graphical interface was developed to provide an easy way for the user to analyse the runoff-erosion simulation results. As a distributed hydrological model, Kineros allows the separate simulation of runoff and sediment yield in each discretized element (channels and hillslopes), and the system developed takes advantage of this to provide a graphical visualization of the results in order to facilitate the understanding of the spatial response of the basin to a rainfall event.



(a)

Post Name	Code	Latitude (Km)	Longitude
Destilaria Bom Jesus	39220000	-8.25	-35.00

Elapsed Time (min)	Observed Sediment (kg/s)
0	0.00
1440	0.00
2880	0.00
4320	0.00
5760	52.82
7200	51.06

(b)

Element Number: 15

Balance Sediment

Entry Sediment	.5379E+10	kg
Sediment Deposited	778437600.	kg
Suspensed Sediment	421.	kg
Out Sediment	.4602E+10	kg

Elapsed Time (min)	Calculated Sediment (k...
0.	.000
1440.	.000
2880.	.000
4320.	.000
5760.	.006
7200.	157.307
8640.	147.019
10080.	34.465
11520.	6.621
12960.	1.650
14400.	1.152
15840.	.591

(c)

Element Number: 15

(d)

Element Number: 15

Fig. 6 Windows of the execution process for estimating sediment yield with (a) observed sediment yield data (step 11), (b) computed sediment yield for the specified element (step 12), (c) observed hyetograph and computed and observed sedigraph (step 13), and (d) observed hyetograph and computed and observed sedigraphs and hydrographs (step 14).

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