Development of an interactive embeddable Geographic Information System (E-GIS) for soil erosion prediction

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Abstract Erosion is a critical and dynamic aspect of any water resources project. A computer model was developed for simulating the dynamic aspects of erosion. The computer model was developed using Borland Delphi and ESRI MapObject components. The model is named E-GIS (Embeddable Geographic Information System), and is specially designed for soil erosion prediction. It consists of six sub-models. The first sub-model (BASIS DATA) is used for managing data for the model. The second sub-model (AKUISISI) deals with data acquisition. The third sub-model is RAMAL. It deals with forecasting erodibility and crop factor coefficients. The fourth sub-model is SIMULASI. Its main function is erosion simulation, and it is the core of the model. The fifth sub-model (SIG) deals with spatial erosion simulation, and the sixth sub-model (LAPORAN) handles the spatial presentation of erosion variables. The model was tested and validated using recorded data from the Jeneberang drainage basin, South Sulawesi, Indonesia.

Key words E-GIS; erosion; Indonesia; Jeneberang basin; simulation and computer model

NOTATION

A = basin area (m^2)
C = land cover factor
E = erosion rate (t ha^{-1} year^{-1})
$EI_{30,\,m}$ = mean monthly erosivity factor (kJ ha^{-1})
$Er_{land\ unit}$ = erosion rate on a land unit
Er_{plot} = erosion rate on a plot
K = soil erodibility
L = slope length (m)
LS = length-slope factor
Lx = determined from: $Lx = \frac{0.5A}{LCH}$
LCH = the total length of channels (m)
N = number of rainfall-days in a month
P = conservation factor
P_T = erosion-control-practice factor for terracing
R = rainfall erosivity (kJ ha^{-1})
R_m = monthly rainfall (cm)
S = slope steepness (m m^{-1})

SR = portion of the drainage basin farmed with straight rows
SRWW = portion of the drainage basin farmed with straight rows and grassed waterways
T = portion of the drainage basin that is terraced

INTRODUCTION

The increasing food consumption in the word accelerates erosion rates. This is due to the intensity of agricultural activity, which requires expansion of agricultural lands. It is reported that the average erosion rate in Asia is about 10–20 t ha^{-1} $year^{-1}$ (Pimentel, 1993). Soil erosion adversely affects crop productivity by reducing the availability of water, nutrients and organic matter, and by restricting rooting depth. GIS has been used to estimate erosion rates in large drainage basins (e.g. Munir *et al.,* 2000). However, owing to the dynamic nature of soil erosion, it is difficult to predict the temporal and spatial patterns in erosion rate, especially in large drainage basins. To overcome this problem it is necessary to develop an interactive computer model that can assist in predicting how the erosion rate varies in space and time (Munir *et al.*, 2001).

MODEL DEVELOPMENT

The E-GIS model consists of six sub-models. The first sub-model (BASIS DATA) is used for managing the database for the model. The second sub-model (AKUISISI) deals with data acquisition. The third sub-model (RAMAL) deals with forecasting simulation; it functions as a knowledge base that deals with determining erodibility and crop factors. The fourth sub-model (SIMULASI) deals with simulation of the spatial and temporal patterns of erosion. The fifth sub-model (SIG) handles the presentation of the spatial and temporal data; it provides the possibility of embedding the geographical data. The sixth sub-model (LAPORAN) deals with output reporting. The structure of the model is shown in Fig. 1.

Database and knowledge base development

A computer database system was constructed for processing and managing the variables for soil erosion prediction in the drainage basin. Input data can be entered into the system via the keyboard or through digitizing map information (Eastman, 1992). The maps that are digitized and on which the GIS is based are the thematic input maps of the model. The database management system was developed using Structured Query Language (SQL). The system is connected to the spatial database by a database engine. The RAMAL sub-model is a knowledge base that serves the whole system, and employs neural network simulation (NNS) for predicting erosivity and crop factors.

Neural network simulation is based on some form of "learning rules" that modify the weights of connections according to the presented input patterns. In this model, the back propagation technique (Kathman, 1993; Maddalena, 1996) is employed in the

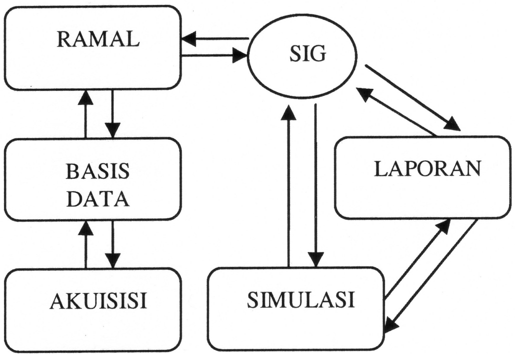

Fig. 1 Structure of the E-GIS model.

NNS. Soil erosion data collected in the field are used as input to train the proposed NNS. All data are normalized into values between 0.0 and 1.0. This is necessary because every neuron in the hidden and output layers of the back propagation employs a sigmoid function with a range of 0.0 to 1.0. The Back Propagation Technique (BPT) is used to set up the learning process of each erosional variable. After the NNS is trained on the pattern associations of input and output factors for the historical data, it generates output patterns when presented with input patterns. In this way, the trained neural network predicts future values of erosivity and crop factors that are based on new sets of input factors.

Development of the distributed erosion model

The distributed erosion model is realized using an interactive computer programming technique that is designed for the model. The E-GIS model was written in the programming language Delphi. Each thematic map was created following the procedure described below. The thematic maps show erodibility, erosivity, and topographic, crop and conservation practice factors. The spatial pattern of erosion is calculated using the USLE (Wischmeier & Smith, 1978):

$$E = R \times K \times LS \times C \times P \tag{1}$$

The erosivity factor (R) was calculated using the equation developed by Bols (1976):

$$EI_{30,m} = 6.119 R_m^{1.211} N^{-0.474} R_{MAX}^{0.526} \tag{2}$$

The result of the erosivity calculations is processed in the neural network simulation model that is programmed in the sub-model RAMAL.

The soil erodibility factor (K) is computed following the nomograph prepared by Wischmeier & Smith (1978). The topographic factor is computed following the formula suggested by Williams & Berndt (1972):

$$LS = \sqrt{\frac{L}{22.13}}(0.065 + 0.0453S + 0.0065S^2) \tag{3}$$

The land-use map is used to determine the C-factor values for each land sub-unit following the table provided by the Department of Agriculture, South Sulawesi (1999).

The *C*-factor is estimated based on the predominant land use. The *C*-factor is highest for bare land (1.0), and lowest for land that is fully covered with straw mulch (0.005). The change of the coefficients can be predicted using neural network simulation in the RAMAL sub-model.

The *P*-factor accounts for onsite practices that reduce the effects of topography, slope length and slope angle, such as strip-cropping, contouring and terracing. The *P* value for each surface unit of land containing various conservation treatments can be estimated using the formula of Williams & Berndt (1972):

$$P = 1.0 \times SR + 0.30\ SRWW + P_T \times T \qquad (4)$$

Computer program

A procedure was developed in the Delphi programming language to provide the ability to embed geographical data into the model. Data analyses are assisted by a database engine that is integrated in the computer program. A listing of the procedure is presented below:

```
procedure TFPeta.BukaData; //Procedure name
var konekdata,datapeta,petatematik,lyr :variant;
namafile,namadir:string;
begin
namafile:=opendialog1.filename;//File extraction
Namadir:=extractfiledir(namafile);
if length(opendialog1.FileName)= 0 then Exit;
konekdata :=CreateOleObject('MapObjects.DataConnection'); konekdata.Database:=namadir;   //Data connection
if not konekdata.connect then exit;
while pos('\',namafile)>0 do
delete(namafile,1,1);
while pos('.',namafile)>0 do
delete(namafile,pos('.',namafile),4);
datapeta :=konekdata.FindGeoDataset(namafile);
if varisempty(datapeta) then exit;
petatematik :=CreateOleObject('MapObjects.MapLayer');
petatematik.GeoDataset(datapeta);
if (not varisempty(petatematik)) then
begin
fpeta.Panel4.Enabled:=true;
fpeta.Panel5.Enabled:=true;
fpeta.Panel4.Font.Color:=clBlack;
fpeta.Panel5.Font.Color:=clBlack;
fpeta.LayerComboBox.Enabled:=true; fpeta.Map1.Layers.Add(petatematik); //Embedding spatial data
fpeta.Map1.Extent:=fpeta.Map1.FullExtent;
fsimulasi.Map1.Layers.Add(petatematik);
fsimulasi.Map1.Extent:=fpeta.Map1.FullExtent;
end;
legenda:=TImage.Create(self);
legenda.parent:=frm;
legenda.Align:=altop;
legenda.Height:=40;
lyr:=Map1.Layers;
UpdateToolStatus(lyr.count);
LayerComboUpdate(0);
end;                    //End of procedure
```

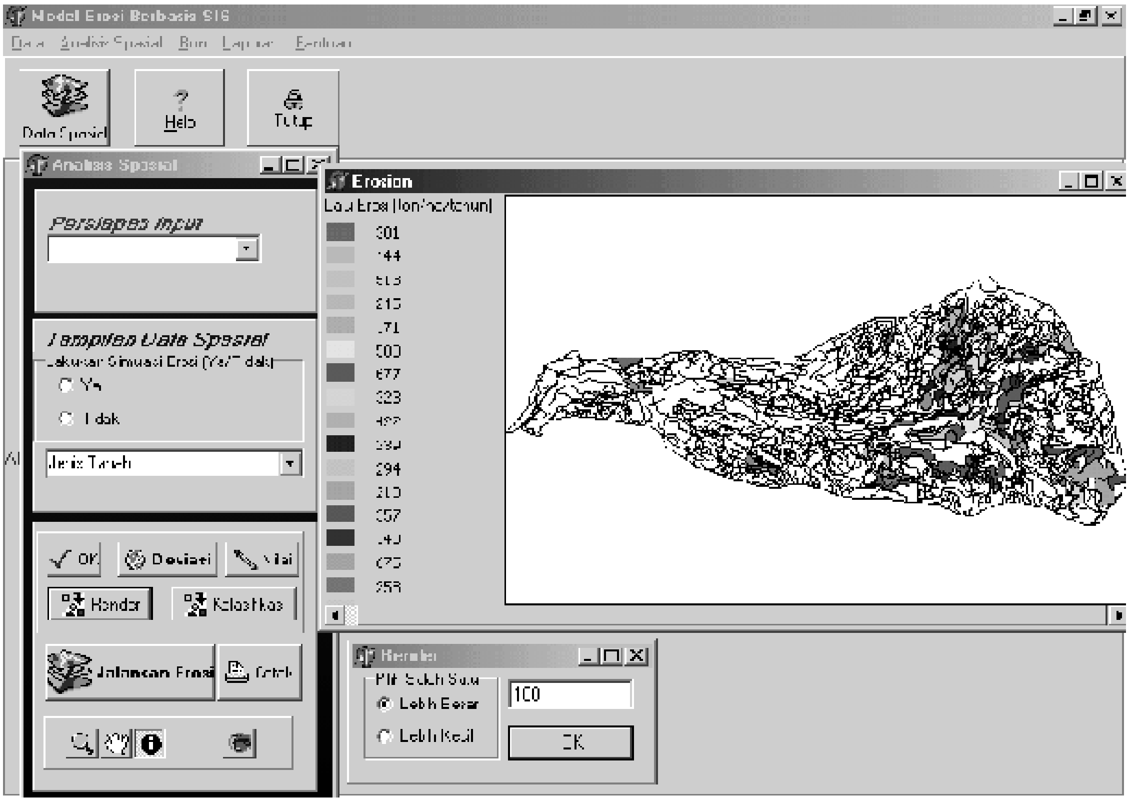

Fig. 2 View of main menu of the program.

The main menu of the program is shown in Fig. 2. The menu is interactive, and can be operated by a user with little computer experience. The spatial data must be in standard GIS format.

Information related to the spatial data can be visualized interactively as shown in Fig. 3. The presented information is generated from the erosion simulation.

The program can also produce a report (Fig. 4). The report contains information on the erosion in each polygon. Decision makers can use the report to decide the most suitable location for a soil conservation project (e.g. to evaluate a land-use scenario or determine the location of a sediment trap).

The program can also be used for simulating erosion in other drainage basins. A help system is integrated in the program. The program therefore can be easily used, even by less experienced users.

The computer program has the potential of being used on the Internet. A future version will be released for developing a national erosion network.

VALIDATION AND TEST CASE

The model was validated in the Jeneberang drainage basin on South Sulawesi, Indonesia. The plots consist of four different land covers (forest, mixed agriculture, grass and without vegetation). The land covers represent existing land use in the drainage basin. Validation was carried out in one year. The plots are 5 m wide and 10 m long.

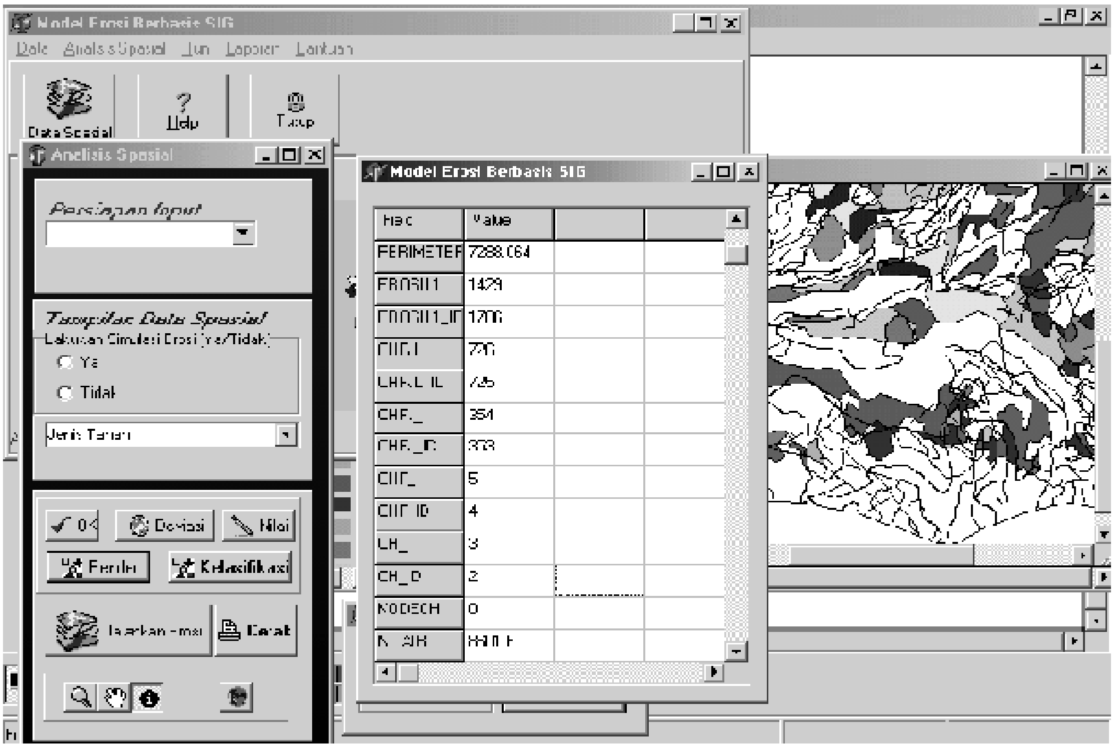

Fig. 3 View of spatial information.

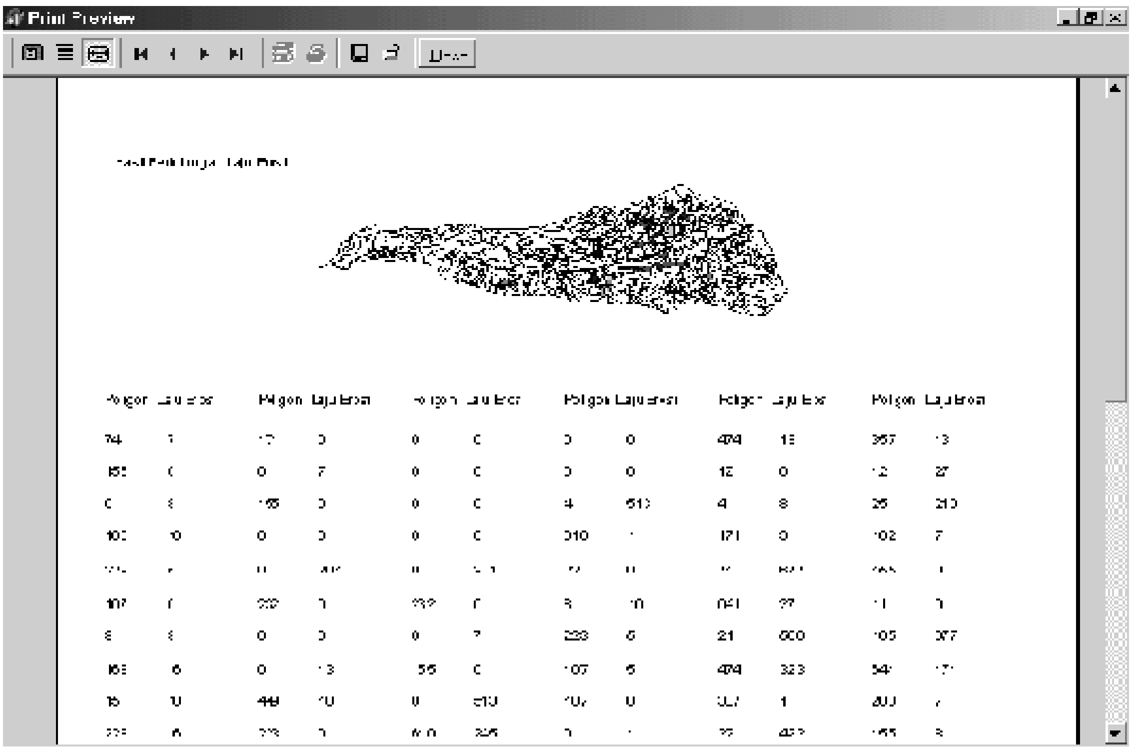

Fig. 4 View of an erosion report.

Table 1 Erosion plot characteristics.

No.	Plot	Erodibility (*K*)	(*LS*)
1	Plot I	0.21	2
2	Plot II	0.21	6
3	Plot III	0.21	5
4	Plot IV	0.21	5

Table 2 Area with an erosion rate greater than 250 t ha^{-1} $year^{-1}$ in the Jeneberang drainage basin (1975–2002).

Year	Area (ha)
1975	1 640.39
1980	1 642.39
1985	2 903.32
1990	1 800.44
1995	2 372.38
2000	2 372.38
2001	3 491.07
2002	4 559.70

The erosion rate on each surface unit (polygon) in the drainage basin can be obtained by extrapolating the plot measurements to the surface units. The method used is presented below:

$$Er_{landunit} = \frac{K_{landunit} \times LS_{landunit}}{K_{plot} \times LS_{plot}} \times Er_{plot} \quad (5)$$

The model was tested by comparing simulated and measured results. The simulated erosion rate for the Jeneberang drainage basin is 1794 m^3 km^{-2} $year^{-1}$, which is very close to the rate measured by the Department of Public Work, South Sulawesi, Indonesia (1999) of about 1810 m^3 km^{-2} $year^{-1}$.

A test was conducted in order to evaluate the performance of the model in identifying the highest erosion rate. The test was conducted using the 1978–2002 data for the Jeneberang drainage basin. Erosion rates are predicted using the sub-model RAMAL. The surface area with an erosion rate greater than 250 t ha^{-1} $year^{-1}$ in the drainage basin is presented in Table 2.

Prediction of erosion rates for the next three years was done using the neural network component of the model. Results indicate that a large increase in the rate of soil erosion would occur in the year 2002, if existing land use practices without conservation were continued. High erosion rates (filled polygons in Fig. 5) are caused, not only by the changing rainfall pattern, but also by a reduction in surface cover.

The maps shown in Fig. 5 can be used to identify priority areas that require conservation treatment. Using the priority map, limited resources can be directed to the areas with the greatest need. It is important to note, however, that such information must not be used as a justification for not conducting erosion control in a non-priority area. Prioritization must be based on need to protect the receiving water body, the requirement for sediment control structures, and the budget allocated to soil conservation projects.

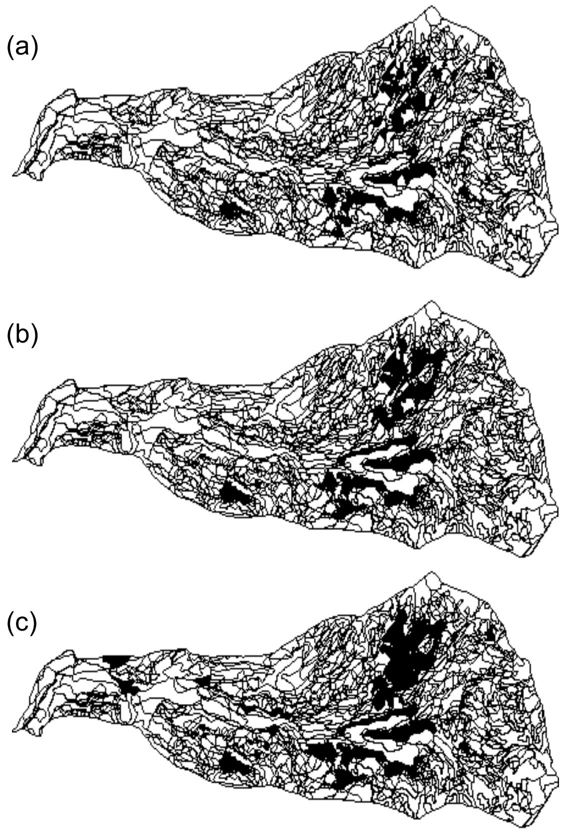

Fig. 5 Spatial variability in erosion rate in the Jeneberang drainage basin: (a) 1975, (b) 1990, (c) 2002. Filled polygons have an erosion rate greater than 250 t ha^{-1} $year^{-1}$. Figures are not to scale.

CONCLUSIONS

The E-GIS model is a powerful model for simulating the spatial and temporal patterns in erosion rate. The model consists of six sub-models that can be used not only for simulating erosion rates under the existing conditions, but also to estimate future erosion patterns. The model is interactive and user-friendly, and is very suitable for simulating erosion rates in large drainage basins. The model has the potential to be applied to other drainage basins.

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