

GIS-based modelling of non point source pollution from agricultural sources.

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Abstract

A mathematical modelling approach is presented for agricultural non point source pollution, based on a GIS paradigm. The capability of GIS technology is exploited so to achieve a detailed description of the study area via simple mathematical relations. The features that make the approach preferable for land use management and planning are highlighted. An application to a case study (the river Savio catchment in Emilia Romagna, Italy) is also given, that shows how the model can be set up using currently available cartography.

Introduction

Automated computing has been giving environmental modellers over the past twenty years very sophisticated tools for the quantitative description of physical phenomena, and now plenty of models with extremely deep conceptual roots and elaborate mathematics can be found cheap or free. A drawback with these kinds of models is they all need plenty of input and calibration data, that often make very expensive their use and don't allow planners to fund a complete use of them in real world case studies. At the same time, environmental planning needs for evaluations time-lumped and specifically scaled in space, and just a few of the details produced by traditional dynamic models. This makes very appealing that modelling approach that capitalizes upon the capability of a GIS, especially the raster ones, for a detailed and spatially distributed description of phenomena and processes via locally simple mathematical relationships. One major advantage of this approach is the limited need for input and calibration data if compared to that of the traditional distributed dynamic models, and the capacity to cope with cartographic information as the one available from local and national authorities: most of the parameters GIS-based modelling uses are just physically measurable entities, and need not be calibrated. For the parameters that still remain to be chosen, a calibration technique can be issued, but it is a goal of GIS modellers to keep model sensitivity to them as low as possible, thus requiring a rougher estimation. In the following, the implementation of a GIS based model of diffuse pollution from agricultural watersheds is described, and a simplified application is made to a case study.

Location of the study area

The study area is the Savio river catchment located in the regione Emilia Romagna near Cesena, Italy. The watershed is basically hilly and mountainous, with elevations ranging from 1400 m asl to 40 m asl, for an extension of about 480 km². Watershed hydrology basically relates to rainfall, and the discharge in the main river ranges from a few liters per second during summer, to some tenths cubic meters in spring and autumn. The 100-year peak discharge approaches 1000 m³s⁻¹(figure 1).

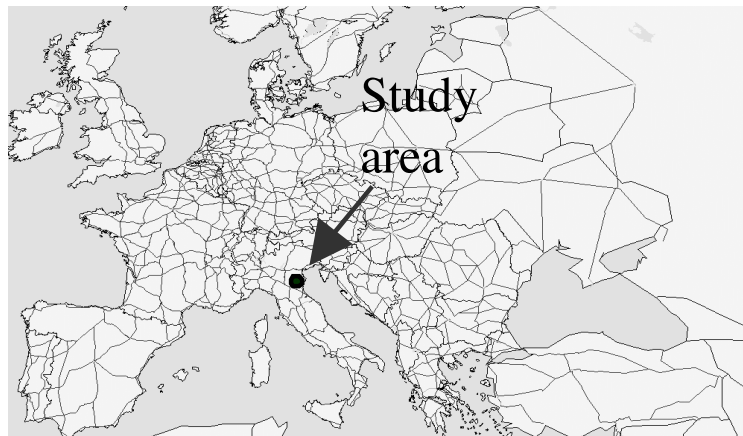


Figure 1 – location of the area

Geological units basically belong to marl and sandstone formations and limestones, with clay deposits also. These are the most favourable terrain for the development of gully erosion processes that appear to be quite common all over the clayey and marly portion of the catchment.

Land use basically consist of orchards and vineyards in the lower, hilly part of the basin, while in areas closer to the divides most of the agricultural land use is represented by cereals (wheat, malt, sorghum) and pastures. In this part of the area woods also cover an appreciable portion of land, often in alternation with pastures and prairies.

Goals and methods

It is the aim of the study to check the applicability of simple data driven modelling to predict diffuse pollution from agricultural sources. It is well known, in fact, that pollutants and especially nutrients come from cultivated land as dissolved in runoff and attached to the eroded sediments. Many models exist to simulate the behaviour of nutrients at the watershed scale (e.g. CREAMS/GLEAMS, AGNPS, SWAT). Most of them are event-oriented. Recently a new version of AGNPS has been issued (AnnAGNPS, 1998) to predict annual effects in a continuous fashion, and is under beta-testing. In all these models, a very detailed description of the processes is performed and requires data about agricultural practices, soil science, hydrology, plant development and so on.

There are anyhow some basic requirements that a model must fulfill in order to be suitable for decision supporting in land planning: (1) capability of describing a process to a satisfactory degree of accuracy, which depends on the aims it is implemented for; (2) capability to give the planner a clear scheme of the consequences of each choice (decision supporting); (3) expert user friendliness and low requirements of data, basically limited to those actually available from local government and environmental protection agencies; (4) capability for producing easily understandable results in a form as non-technical as possible, so to become a basis for public discussion and participative planning; (5) availability of easily standardizable calibration procedures to extend the setup of the model to different areas than the training one with minimum extra knowledge required.

GIS technology is now common among the public administrations. So far, only the capability of a GIS to store and retrieve data has been exploited. Time has come to use this technology for the analysis of land and environmental systems, as a support for ordinary planning and not just as single research case studies, and the present article aims at giving an example of the use of GIS modelling for decision supporting. The dataset used for this case study comes from the Regione Emilia Romagna Cartography and Geological Survey and from the Regional Environmental Protection Agency (ARPA). Information was retrieved from the following maps: (a) soil map (scale 1:250000); (b) CORINE land cover (scale 1: 100.000); (c) elevation (scale 1: 50.000) ; (d) hydrography and rivers (scala 1:10.000).

It must be noticed that the coarser data layer (the soil map) is very important in the model response, thus dropping the whole analysis to a detail as achievable at a 1:250.000 scale. This makes clear that the results must be looked at as orientative, and the numerical values obtained are nothing but a first guess estimate. This doesn't invalidate the whole approach, but rather stresses the expert-system-like framework required for these kinds of evaluation: once a new and finer data layer is provided, the calculations can be directly re-run, keeping the relationships between the used objects unaltered. In the specific case study, the procedure has been set up, while further refinements of the data sets will be available soon, thus allowing better results in the predictions. The data were available from an Arc-INFO system and were processed using ILWIS 2.23 software. In further developments, finer analysis tools supported by this software will also be used.

Description of the model used

For the prediction of non point source pollution, it is necessary to quantitatively describe the mass fluxes of water and eroded sediment and the concentration of dissolved or sediment attached nutrients. As far as erosion was concerned, the well known Morgan approach (Morgan et al., 1982) was chosen due to its stronger physical base. The erosion process is depicted through two phases, namely the water phase and the sediment phase, and a distinction is made between sediment detachment by raindrops and sediment transport due to overland flow. This approach provides tools to detect potential sediment redeposition areas within a watershed, but some development of the original field scale algorithm need to be implemented before this relative advantage be effective. Once the detachment and transport rates are assessed, the model takes the minimum of the two as an estimate of the net erosion from a cell. In the following, the basic relations are summarized.

Water phase (fig.2)

Input requirements:

R: annual rainfall (mm).

R_n: number of annual rainy days

I: representative rainfall intensity (mm h⁻¹).

An average value of 30 mm h⁻¹ was assumed according to Morgan's (1995) suggestions for strongly seasonal climate areas.

E_t/E₀: actual to potential evapotranspiration ratio

MS: moisture content of the soil at field capacity (% w/w).

BD: bulk density of the first soil layer (g cm⁻³).

RD: rooting depth of the first soil layer(m): in our case this is the same as the depth to the base of the A horizon

Model computation:

E: kinetic energy of rainfall (J m^{-2}).
Q: volume of surface runoff (mm).
 For E, the following formula holds:
 $E = R (11.9 + 8.7 \log_{10} I)$

WATER PHASE

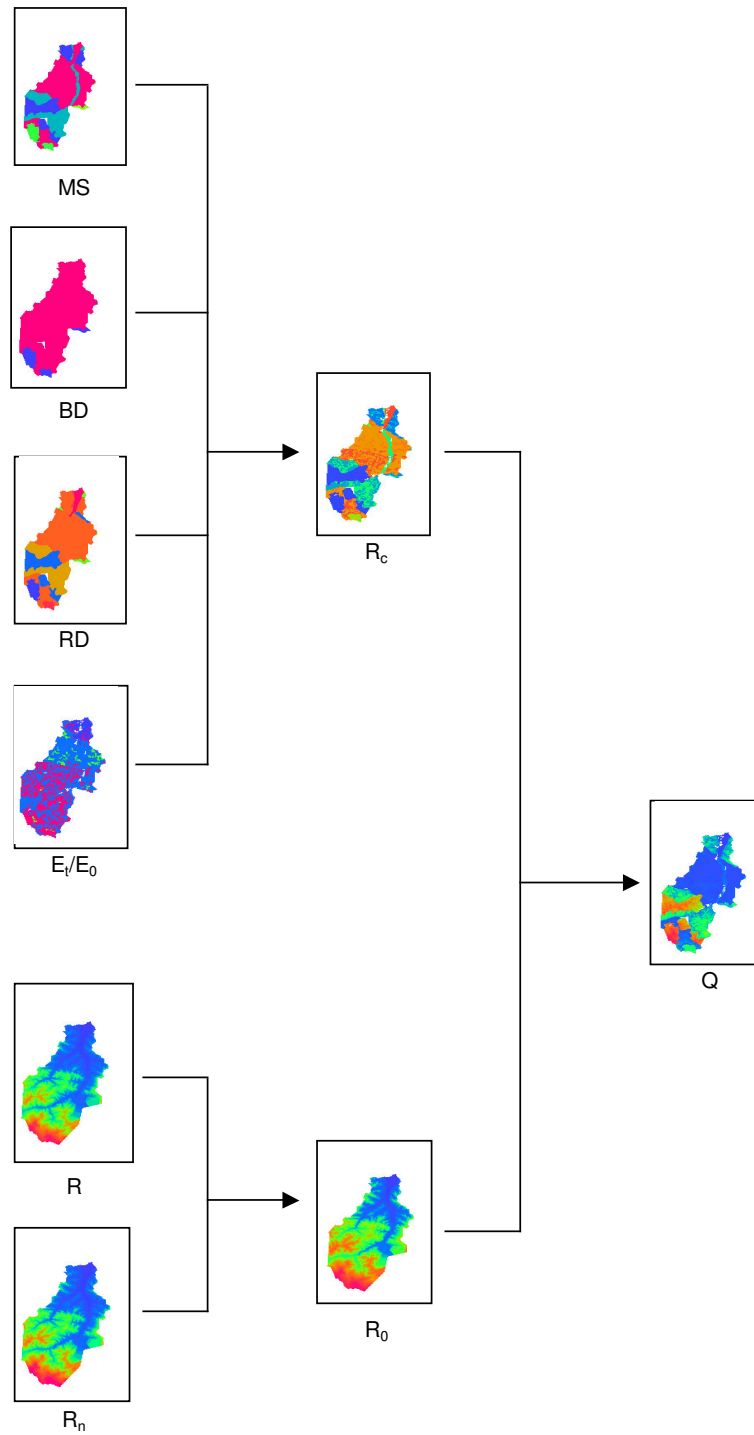


Figure 2- water phase modeling scheme

As far as Q is concerned, in principle the study at the watershed scale would require at first the delineation of drainage directions and accumulation areas for all the pixels, and then the routing of infiltration excess all over the catchment (as suggested in the SEMMED approach: see Morgan, 1995). This was not done due to very raw elevation data, and will be the first model development as soon as a good DTM will be issued by the Regional Cartography and Geological Survey, which is planned in short times. In this first application, the original field scale formula was used to predict Q:

$$Q = R e^{-R_e/R_0}$$

where:

$$R_e = 1000 MS \cdot BD \cdot RD \cdot (E_t/E_0)^{0.5}$$

$$R_0 = R/R_n$$

It is apparent that, when a more suitable Q map will be computed as said before, this won't involve the whole model to be rebuilt, but just to recalculate the maps keeping all the relations unaltered.

Sediment phase (fig.3)

Input requirements:

- K:** soil detachability index ($g J^{-1}$).
- A:** precipitation interception rate (-)
- C:** land cover and management practice factor (-)
- S:** hill slope (radians).

Model computations:

- F:** detachment rate($kg m^{-2}$).
- G:** overland flow transport capacity($kg m^{-2}$).

The following relations hold:

$$F = K (E e^{-aA})^b \cdot 10^{-3}$$

$$G = C Q^d \text{sen}S \cdot 10^{-3}$$

where :

$$a = 0.05;$$

$$b = 1.0;$$

$$d = 2.0.$$

SEDIMENT PHASE

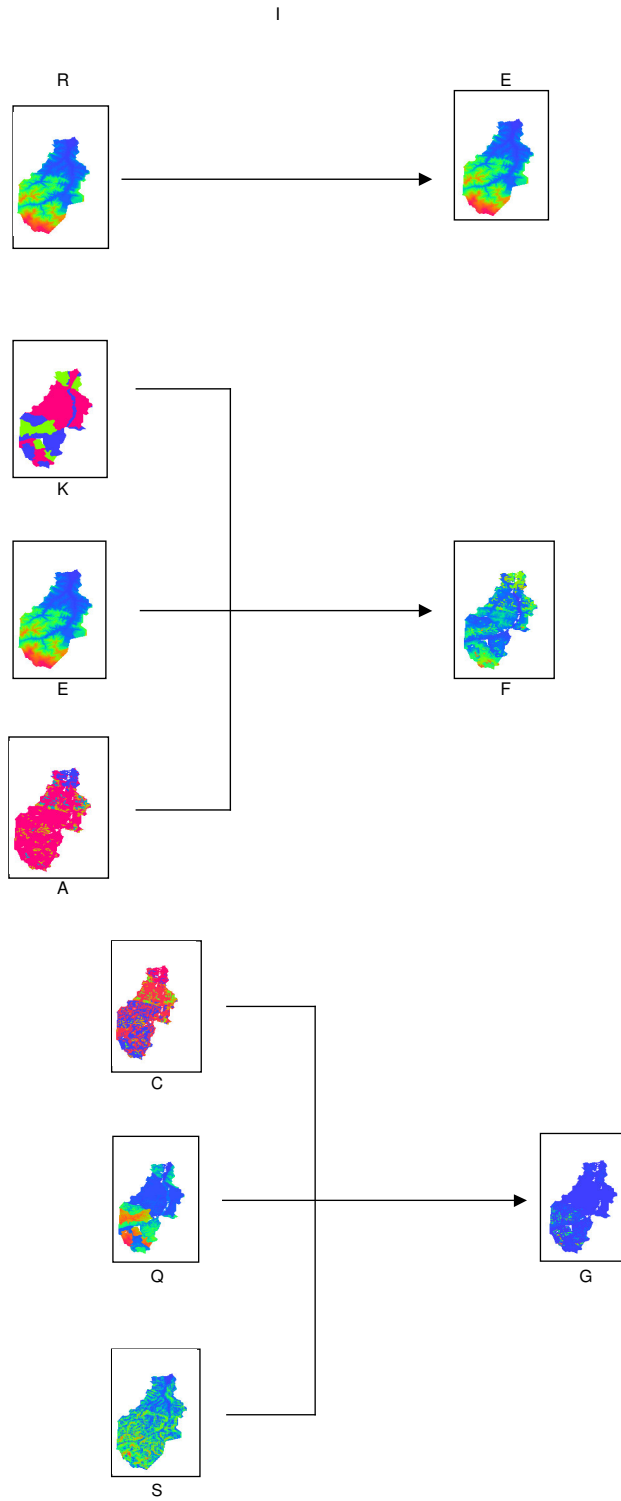


Figure 3 – sediment phase

In a complete implementation of the procedure, a comparison of the transport capacity of each pixel (computed using an improved estimate of Q as specified) with the sum of the whole amount of sediments from upslope and

the detachment rate inside the pixel will be done. The downslope amount of sediment yield from each pixel will be thus the minimum of the two quantities. For the purpose, kinematic analysis of the catchment is required using neighbourhood operators or other common tools in the GIS.

The analysis was performed using a raster representation of the catchment with 50x50 m square cells. The rainfall data refer to seven rain gauge stations along the main stream line, as reported in the following table.

Table 1. Annual average rainfall for the seven measurement points used.

Station	Elevation asl (m)	Annual average rainfall (mm)	Rainy days in a year
Verghereto	812	1304.2	111.0
Bagno di Romagna	495	1283.9	109.1
Terzo di Carnaio	704	1197.1	101.5
Diga di Quarto	325	860.6	94.9
Monte Jottone	442	848.6	84.7
Luzzena	312	854.2	77.0
Cesena	44	829.4	84.7

A linear regression was calculated between elevation and annual rainfall, and the resulting equation (with linear regression coefficient $R^2=0.66$) is: $y = 0,7086x + 708,19$ where y is mean annual rainfall and x the elevation a.s.l. A similar regression was computed between elevation and rainy days in a year ($R^2=0.53$). The resulting equation is now : $y = 0,0374x + 77,977$, with y =mean annual number of rainy days. Parameters MS, BD, K were chosen according to the soil texture classes, as shown (tab.2) in literature. Parameter RD was chosen on the basis of the *Note illustrative della Carta dei suoli 1:250,000*, a description of the mapping units issued by the Regione Emilia-Romagna (1994). Of course the map scale (1:250,000) supported just a first guess estimate, as specified.

Table 2. Soil parameters (Morgan, 1995).

Soil type	MS	BD	K
Clay	0.45	1.1	0.02
Clayey Loam	0.40	1.3	0.40
Silty clay	0.30	1.2	0.30
Sandy Loam	0.28	1.2	0.30
Silty Loam	0.25	1.3	0.30
Loam	0.20	1.3	0.35
Loamy sand	0.15	1.4	0.20
Sand	0.08	1.5	0.70

Land use related parameters were assigned also by literature indications (tab.3).

Tabella 3. Land use parameters (Morgan, 1995).

Land use	A	E_t/E_0	C
Seeding	30	0.65	0.3
Orchards	17	0.60	0.35
Woods	30	0.95	0.002-0.004
Pastures	20	0.75	0.15
Grass, shrubs	25	0.65	0.2
Bare rocks	0	0.05	1

The slope map was calculated from a DTM issued by ARPA, made from a 250x250m elevation data grid. The rain and rainy days maps were also derived from the DTM by using the regression equations.

Table 4 summarizes the estimated values obtained after computing soil erosion with the 'field scale' algorithm.

The nutrient loading was estimated using the algorithms derived from model CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems, USDA, 1980) and also used in AGNPS with minor changes. A possible different choice might have been the algorithms of the SWAT model, but CREAMS was preferred because of the more complete documentation and experimental data. It must be recalled that nutrients in soil have different fates according to physico-chemical soil features, modalities of fertilization, plant uptake, washout and erosion due to overland flow. Phosphorus, in particular, shows a lower mobility and is basically

transported as sediment attached, while nitrogen (especially as nitrates) is more subject to washout. In the following, the symbol (-) is used when referring to N o P (E.g.: SED- = SEDN o SEDP).

A) *Estimate of the sediment attached nutrients*

An enrichment factor is computed so to keep track of the granulometric classification due to sediment transport, with the formula:

$$ER- = A- \cdot SED^{B-} (-)$$

The sediment attached nutrient loading is then computed by:

$$SED- = SOIL- \cdot SED \cdot ER-$$

where:

SED-: sediment attached nutrient load (kg ha⁻¹).

SED: sediment load by soil erosion (kg ha⁻¹).

SOIL-: in-soil concentration of the nutrient (kg/kg of soil).

Table 4. Annual soil loss estimated using Morganfield-scale approach in the Savio catchment.

Land use	Annual soil loss (t/ha/year)
Seminativi	4-22
Frutteti e vigneti	2-35
Prato-pascolo	<1-25
Boschi	2-5
Incolto	25-35
Rocce nude	118-134

For nitrogen it has been assumed a concentration of 0.002 kg/kg of soil; for phosphorus, 0.00055kg/kg of soil.

A-;B-: parameters that have been assumed equal to 7.4 e -0.2 respectively for both N and P, according to the guidelines given by the CREAMS manual for a first estimate.

B) *Nutrients dissolved in runoff*

The amount of N and P in runoff (kg m⁻³) is computed as follows:

$$RON = C_2 \cdot EXKN_2 \cdot Q \cdot 0.01$$

$$ROP = C \cdot EXKP_2 \cdot Q \cdot 0.01$$

Where:

EXK-₁: extraction coefficient for infiltration

EXK-₂: extraction coefficient for surface runoff.

These are given by:

$$EXKN_1 = d \cdot POR \cdot K_1$$

$$EXKN_2 = d \cdot POR \cdot K_2$$

$$EXKP_2 = d \cdot POR \cdot K_2$$

being

K₁: infiltration rate.

K₂: runoff rate.

POR: porosity of the soil, assumed to be 40%.

d: depth of the first soil layer, assumed as 10 mm.

Average values as suggested in CREAMS are assumed for the extraction coefficient, thus bypassing the discussion on which value to choose for **K₁** and **K₂**.

$$C_2 = (C_1 - C_r) / K_2 \cdot Q \cdot (1 - \exp(-K_2 \cdot Q)) + C_r$$

$$C = (C_1 - C_r) / K_2 \cdot Q \cdot (1 - \exp(-K_2 \cdot Q)) + C_r$$

$$C_1 = (C_0 - C_r) \cdot \exp(-K_1 \cdot F) + C_r$$

C_r: concentration of the nutrient in rainfall (assumed =0)

C₀: concentration of N or P in the water stored in the first layer of soil (kg m⁻³).

F: infiltration of the event (mm).

Q: total runoff for the event (mm)

The above expressions come from a water balance during the single event. For the computation of the amount of infiltration **F**, actual evapotranspiration **ETR** was computed using Turc's formula, and then performing a hydrological balance computation:

$$ETR = P/\sqrt{0.9 + P^2/L^2}$$

Where $L = 300 + 25 \cdot T + 0.05 \cdot T^3$ (mm)

P = mean annual rainfall(mm)

T = mean annual temperature (°C)

Then a runoff coefficient was computed (c_{SCS}) according to the well known SCS Curve Number Methodology, after making a cross map computation for land use and soil texture data maps. In order to get reasonable values of the runoff coefficient, a representative rainfall amount equal to about 5 times the average rainfall per rainy day was used as the event rainfall amount the method asks for.

Lastly, runoff was computed as $Q=(P-ETR)*c_{SCS}$. Infiltration F is the difference in :

$$F= P-ETR-Q$$

when storage capacity in soil is neglected. The scheme of the procedure is summarized in fig. 4.

It must be stressed that runoff Q here calculated is different from the one used in the erosion model. The inconsistency is due to the choice of using the original algorithm for the computation of erosion-effective runoff, in that a deeper insight in the question can only be had with more detailed data. Anyhow, since the value of Q as computed in the erosion model takes in account all hydrological losses, it is impossible to evaluate infiltration from the difference between rainfall and the computed runoff. When adequate data for a more precise modelling will be issued, the inconsistency will be removed and a basic hydrologic balance and routing will be performed prior to any other erosion and nutrient loading evaluation. Figures 5 and 6 summarize the logical flowsheet hereby followed for the model.

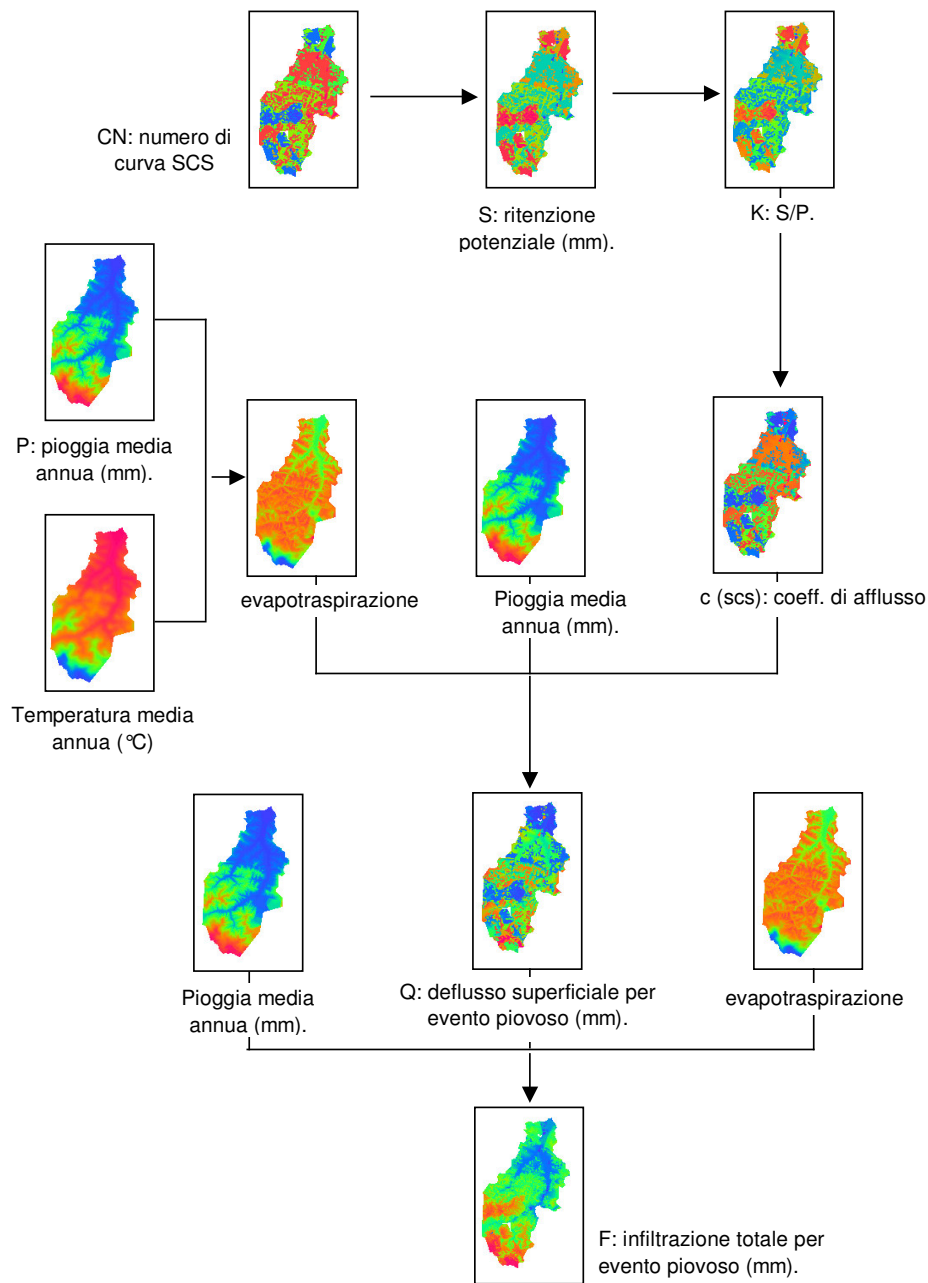


Figure 4 – distributed hydrologic balance

Results

The total nutrient load from a cell is given by the sum of the sediment attached nutrient and the runoff-dissolved one. For instance, one can represent the final nitrogen sources map. If one looks at the histogram of the map, nitrogen is estimated as about 10 to 60 kg/ha per year, while phosphorus ranges from 2 to 15 kg/ha per year. The obtained values seem in excess with respect to registered literature values. The tendential overestimation may be interpreted as due to considering the whole annual rainfall as contributing to the loading, while only a part is effective due to the limited periods of the year in which nutrients are in soil and not yet adsorbed by the crops. Further reasons of uncertainty are introduced by assuming average values for the parameters, in absence of information for an uncertainty assessment. At last, the computed maps must be regarded as *a physically based land classification* with respect to the potential origin of nutrients, already useful and usable for the ranking of intervention priorities at the watershed scale, but not reliable as far as “what if” type issues are

concerned and quantitative assessment is required. For this goal, in the following are listed some lines of research development.

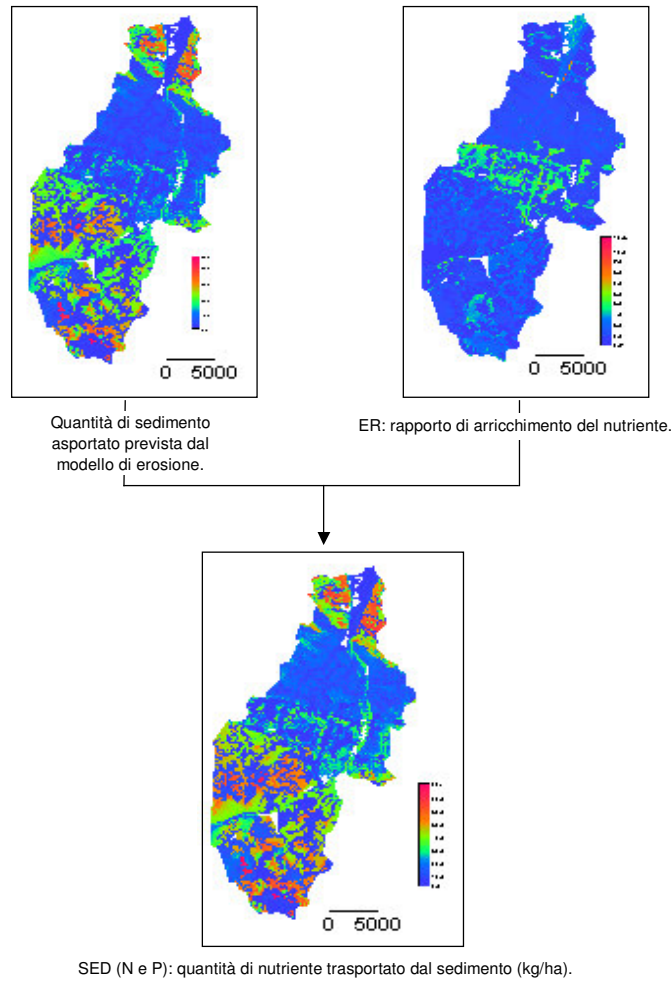


Figure 5 – sediment-attached N and P load computation

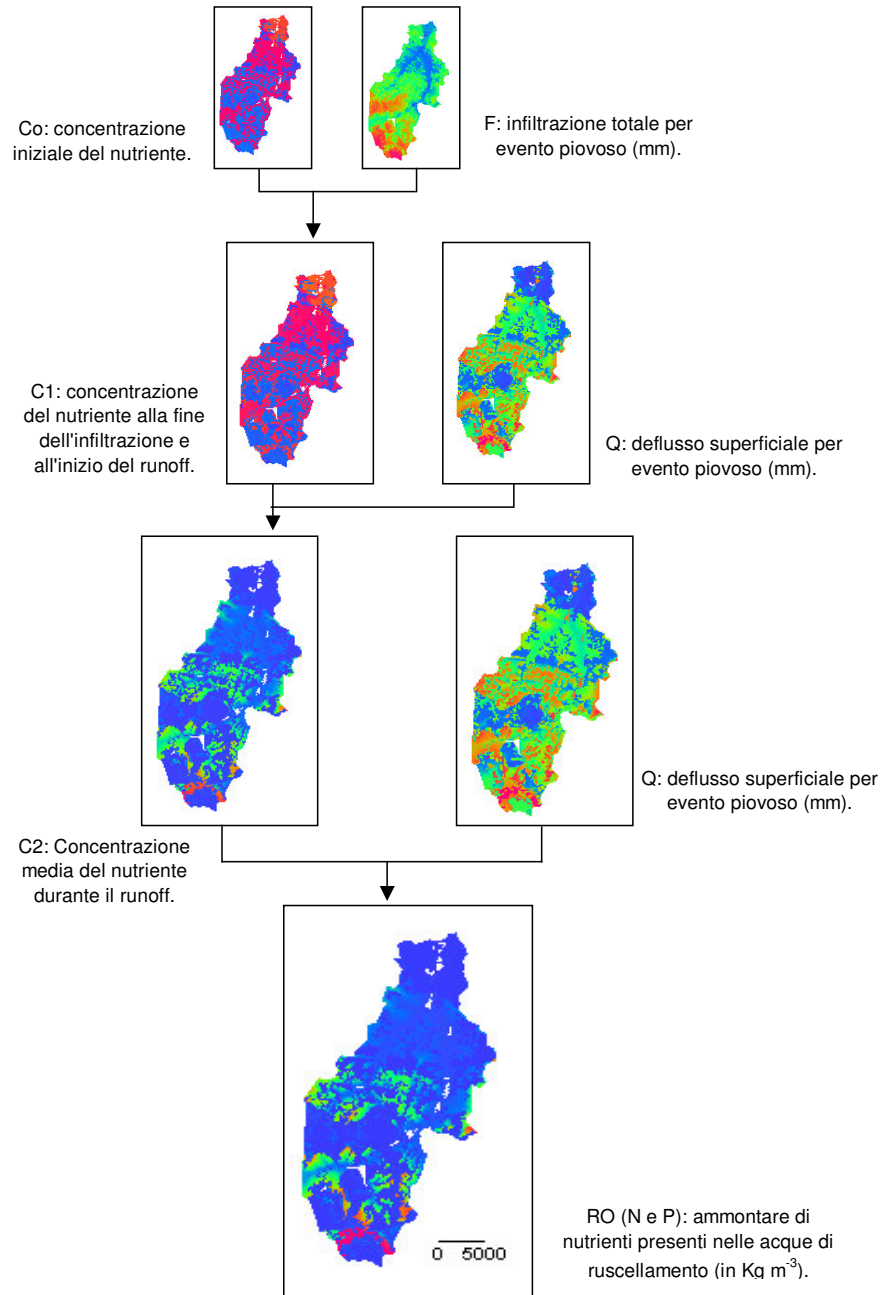


Figure 6 – dissolved N and P load computation

Conclusions

In principle, a raster GIS can be used to model hydrology, erosion and non point source pollution both at the single event and at the lumped annual temporal level, using the concepts of kinematic routing of mass fluxes and distributed cell based submodels for the main hydrological processes (evaporation, transpiration, infiltration...). Such distributed yet simply treated GIS based models are of great interest when planning of agricultural management practices and hydrological enhancement of the catchments are concerned. Also when planning the combating of diffuse pollution it is of great interest to map processes and to assess where interventions are most effective with respect to global results yet depending on local contributions, such as a stream quality standard. The preliminary study presented here has shown that results can be extracted from currently available information and cartography, and that a user friendly and highly interoperable output can be given using common packages as raster GISs. Many things, however, need to be analysed yet: future research will be performed about the following lines of action.

- Reliable and properly detailed data acquisition, by integration of the soil map with soil samples from the different mapping units
- Deeper insight in the parameters used to describe soil behaviour such as erodibility/detachability
- Stronger hydrological characterization of the catchment, with emphasis on the distribution of rainfall-related data and all other hydrological parameters

It must be understood that the present work is just a first demonstration, that will be integrated at the model development level by:

- (1) a check on the validity of the rainfall energy equation; (2) a consistent and detailed hydrological submodel achieved by delineation of the local drainage network (Burrough,1998; Pistocchi,1998), kinematic routing of runoff, and distributed hydrological losses description; (3) a consistent consideration of the whole amount of sediments upcoming a cell (by performing a sediment routing via the previously delineated local drainage network) in the balance of soil erosion according to Morgan.

It must be also noticed that further developments might be used for the estimation of a nutrient load to groundwater if proper infiltration models are used.

In conclusion, GISs offer at present the right framework for distributed watershed modelling to be used in land planning. It is a task for the future making all the capabilities effective.

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