Artificial Intelligence Techniques applied to Radarmeteorology and Soil Erosion Research

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1 Introduction

Rainfall erosivity is a crucial parameter for soil erosion assessment. It can trigger topsoil removal, leading to loss of agricultural potential and land degradation. This paper describes a new approach to derive the value for rainfall erosivity from weather radar data by using distributed cellular agents.
Rainfall energy is used in standard erosion formulas such as the Universal Soil Loss Equation (USLE) and its regional variants as a means to measure rainfall erosivity. To calculate erosivity values, rainfall data need to be recorded. In cases where the entire area of interest cannot be covered, interpolation from the available data becomes necessary. When convective rainfall events are to be analysed, both a high spatial and a high temporal resolution is advisable.

2 Erosion and data sources in South Africa

The Republic of South Africa is facing the reduction of agricultural potential by loss of topsoil because of soil erosion. It is imperative for effective soil conservation strategies to know when and where actual soil erosion losses occur.
The weather situation of southern Africa is dominated by convective precipitation patterns. The convective cells are prone to cause heavy, yet spatially isolated precipitation events. This results in a spacially and temporally fluctuating patchwork pattern of the erosivity values.
The author whishes to express his gratitude to the South African weather service (SAWS) for providing radar data for a doctorate thesis [1], upon which this publication is based, to the DAAD for funding the corresponding research in South Africa and finally to the DFG for supporting this publication.
The processed radar data were provided as meteorological data volumes (MDV). This data format is used worldwide for radarmeteorological processing and storage. Therefore the approach described for erosivity modelling in GRASS GIS is not limited to a South African scenario.

3 The Model

The Rainfall Erosivity Index (REI) provides a way to analyse the dynamic structure of rainfall events. It evaluates the total amount of precipitation, its highly erosive parts and derives an index value for each precipitation event [3]. The index requires a gauging device for each raingauge station, which can be implemented as an algorithm to be applied to recorded data sets.
The original German research project applied the REI algorithm to data from stations of raingauge networks, interpolating daily and monthly maps from the accumulated index values of the individual rain gauges [3]. The results show that the mapped patterns only provide limited coverage of the suspected true dynamics of the convective precipitation pattern and its erosivity field [1]. So far, through the results of the REI calculations new questions have been raised, which could not be answered by the processing of raingauge network data.
By using weather radar data most of the previous shortcomings can be avoided, since they provide consistent mapping without spatital interpolation. The South African precipitation data has a maximum spatial resolution of 1 km^2 , recorded in five minute intervals.
So a „virtual raingauge network" model, based on the radar data cells, has been created. It consists of software agents which perform REI-calculations once rainfall data become available for its location [figure 1].

Figure 1: Flowchart of the processing chain for rainfall erosivity index values.

4 Implementing the Model in FOSS

Modelling the REI-Algorithm described above within GRASS GIS was found to be challenging by solely relying on GRASS GIS' current capabilities:
From the limited perspective of a singular virtual raingauge all rainfall pulses of a precipitation event must be indiviudally recorded before the index calculation can be done. This requires storing them in a list, the length of which remains unknown until the precipitation event is over. Since this applies to all agents at any time, such a list of variable length must be assigned to any spatial cell. In fact, the derivation of the erosivity value requires several similar lists during the final index calculation.
Modelling structures of this kinf in map algebra (**r.mapcalc)** is not very elegant. Limitations on the maximum stack depth must be defined and a large number of raster maps would be needed to hold the temporary variables. This makes the model non-intuitive and unnecessarily complex.
Instead, the C-Language Integrated Production System (CLIPS) was accessed via high-level (loose) coupling (CAPE and GRASSCAPE Open Source Projects) to provide the required functionality without reinventing the wheel: An object oriented implementation of the virtual rain gauges as cellular agents with internal states was created within the CLIPS-environment. Each agent will start its data processing once the first rainfall pulse reaches its location. It will continue with its calculations and finish as soon as the rainfall event ceases. It then derives an erosivity index value. This value can be retrieved by the GIS, making spatial-temporal mapping possible. In the meantime the agent returns to its initial state, waiting for a subsequent rainfall event [Figure 1]. Thereby maps of precipitation and erosivity are created at each time interval. They can be summed up to totals and can be used to create animations [Figure 2].
Since the radar data are available in real-time („nowcasting“), erosivity calculations could be performed almost simultanously. This provides new options for ground truthing in the field.

5 Results

Results from the processing chain are shown for the Liebenbergvlei Catchment in the Free State Province. The catchment is under a single radar umbrella (MRL-5 Radar, X-Band).
Consecutive mapping of erosivity values show trailing linear patterns, following the precipitation fields [Figure 2]. This can be explained by the agents behaviour: When a rainfall field passes over an area, all affected gauge-agents become active. Once the field has passed over, they all flag/present their index values simultanously.
Daily totals of precipitation and erosivity [Figure 3] show footprints of pronounced precipitation from convective cells. Within these paths significant changes appear in the erosivity field's signal strength.

Figure 2: Spatial and temporal development of reflectivity and erosivity patterns in the Liebenbergvlei, South Africa (December 15th, 1998).

Figure 3: 24h totals for radar reflectivity, derived precipitation and inferred erosivity (Liebenbergvlei, MRL-5 Radar, December 15th, 1998). All three daily totals show artefacts in the southern area which are caused by ground clutter (topography echoes of mountaineous areas).

When the rainfall and erosivity totals are merged to composites [Figure 4:

erosivity as altitude, rainfall totals as colors], patterns of spatial distribution emerge: Zones of strong precipitation are matched by erosivity peaks, just as expected (green frame in figure 5). But the picture changes for reduced amounts of precipitation - The red frame in figure 5 shows a prime example for this phenomenon: In an area of pronounced erosivity are two raster cells standing out with similar high erosivity totals: One shows a strong rainfall total (red), while the other cell reaches a similar erosivity level, but with much less precipitation input (white). This demonstrates that the agent-based approach is capable of deriving both amount- and rhythm-based erosivity index values.

Less outstanding but also significant are the brown and yellow frames in figure 4: They mark erosivity peaks recorded in greater distances from the radar antenna. The amount of recorded precipitation information is generally lower in these regions. The last section will will explain in more detail why his provides even more potential of agent-based modelling for weather radar data.

Figure 4: Rainfall totals (colors) overlaid on the erosivity landscape (December 15th, 1998)

6 Conclusion

For the first time, it is possible to visualize and analyse erosivity indices in almost real-time and full spatial coverage. This is achieved by the use of radar-rainfall data in conjunction with an agent-based approach modelled in FOSS. For the case of the proposed REI formula, the basic assumption has been verified that this approach is able to measure the erosivity potential of individual rainfall events. However, the REI-parameters must be calibrated before they can be used in quantitative studies. They were not derived from empiric data. Since many different erosivity indices exist, the GIS/Agent-environment can serve as a testbed for comparative studies: Based on identical precipitation input the results from different index-algorithms can be computed and compared against each other. Groud-truthing in the field can be used as a reference. Flexible agent-based modelling is a promising add-on capability for GRASS GIS. It remains to be explored whether distributed artificial intelligence techniques can be effectively realized in R or if specialized environments such as CLIPS or SeSAM are preferrable.

7 Next steps

The availability of spatially continous radar-derived precipitation fields is a tremendous leap forward for the modelling of soil erosion parameters. However, it is not a miracle cure since radar data come with their own limitations and biases. The most striking flaw is the decreasing amount of information with increasing distance from the sensor. Because of the scanning angle of the radar antenna, the ability to infer rainfall decreases with distance. This is illustrated by two figures: In Figure 6, a voxel visualisation of a threedimensional radar-scan shows the stepped underside of a reflectivity field. This effect is caused by the lowest radar scan level. Precipitation information cannot be gained from underneath this radar horizon. The pseudo-cloud voxels merely help to mark the invisible border as the phenomenon is independent from the displayed weather situation. This results in a significant decrease of information with increasing distance from the radar station.
Figure 7 demonstrates this phenomenon [same data used for elevation and color], displaying a cross section through a 24 hour radar precipation total: The stepped rings are perceptible, especially in the right part of the image: The recorded rainfall amounts are affected by radar geometry effects. Since these effects are known, they might be compensated for by parameter-tuning of the REI-formula. The required knowledge could be made available to the agents.
Apart from the necessary field evaluation of the erosivity results provided by the agents, further knowledge such as slope, soil texture and vegetation cover can be embedded in cellular agents. This makes this approach a base for an agent based modelling of soil erosion processes.

Figure 5: Voxel visualisation of pseudo-clouds rendered from three-dimensional reflectivity data. The underside of the cloud structure in the foreground show the steps of the lowest possible radar scan horizon.

Figure 6: The radar geometry and data sampling procedures affect the derived precipiation totals: Pseudo-3d visualisation of the rainfall totals from December 15th, 1998. Same data is used for elevation and color. Note the ring-structures.

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