Temporal disaggregation of precipitation data for modelling soil erosion in landuse change scenarios

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Abstract

Landuse, rainfall and runoff processes strongly influence erosion processes in Alpine regions. The currently developed erosion component of the Global Change Decision Support System DANUBIA will provide a tool to quantify water erosion under landuse change scenarios. The model reacts on high-resolution precipitation data that is not available in the current implementation of DANUBIA. The climate scenario engine of DANUBIA disaggregates rainfall from datasets measured three times a day (*Mannheimer Stunden*) to an hourly resolution. This leads to an underestimation of rainfall intensities, especially for short-term storm events. To overcome this problem, a cascade model was applied to regional rainfall data.

Keywords: cascade model, climate change, erosion, rainfall, temporal disaggregation

1 Introduction

The modelling framework DANUBIA of the GLOWA-Danube project represents an integrated decision support system for future changes in the water cycle of the Upper Danube Basin (www.glowa-danube.de). Further information about DANUBIA is presented in Mauser & Muerth (2007). Beside the modelled water, matter and energy fluxes, a module is developed within the land surface component, to simulate erosion processes. The module consists of the physically based model Erosion3D developed by Schmidt (1991) and extended by von Werner (1995). Particle detachment and transport is calculated using momentum fluxes of runoff and rainfall. Rainfall intensity and resulting runoff cause an exponential increase of soil loss (Schmidt et al. 1996). Therefore supplying the model with high-resolution rainfall intensities is important.

A climate scenario engine provides meteorological input data for DANUBIA. It operates on stochastical re-arrangement of historically measured meteorological data (1970–2006) to generate future climates based on IPCC trend predictions (Mauser et al. 2007). As input data measurements from 257 climate stations are available only three times a day (*Mannheimer Stunden*, i.e. 07:30, 14:30, 21:30) they require temporal disaggregation and spatial interpolation. Generated climate scenarios are fed into the AtmoStations component of DANUBIA for temporal disaggregation (figure 1). Events are classified in two different types:

- advective events with long duration and low intensity (prevailing in spring and autumn). An event is considered advective, if precipitation occurs on two or more succeeding timestamps.

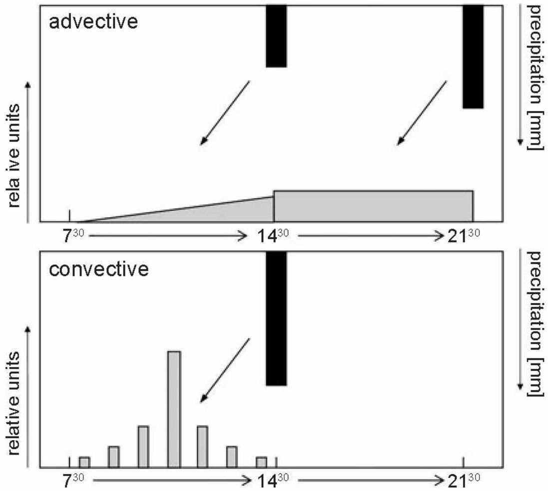

Figure 1: Temporal rainfall disaggregation depending on rainfall type (edited after Ludwig 2000).

- convective events of short duration and high intensity (dominating in the summer months). An event is considered convective, if precipitation occurs only on one timestamp.

Depending on the type of rainfall a defined procedure disaggregates the rainfall into hourly values:
- advective type: beginning or ending rainfall is split up linearly in its associated interval with increasing/decreasing multiplication factors;
- convective type: multiplication factors divide rainfall in a bell-shaped form with a maximum equal to the half of the precipitation sum.

Problems arising from this disaggregation method are mainly reduced intensities of convective events in summer that trigger erosion. In order to gain more realistic intensities from low-resolution precipitation data, a cascade model was implemented and is tested for application within the AtmoStations component in DANUBIA.

2 Methodology

2.1 The model

The model used for rainfall disaggregation is a microcanonical random cascade model with exact conservation of mass after Olsson (1998). This section summarises the basic theory of the cascade model. For further information the reader is referred to the papers of Olsson (1998) and Güntner et al. (2001).

Based on characteristics of rainfall sequences in a continuous, high-resolution time series of rain gauge data, the model collects empirical statistics of the event's

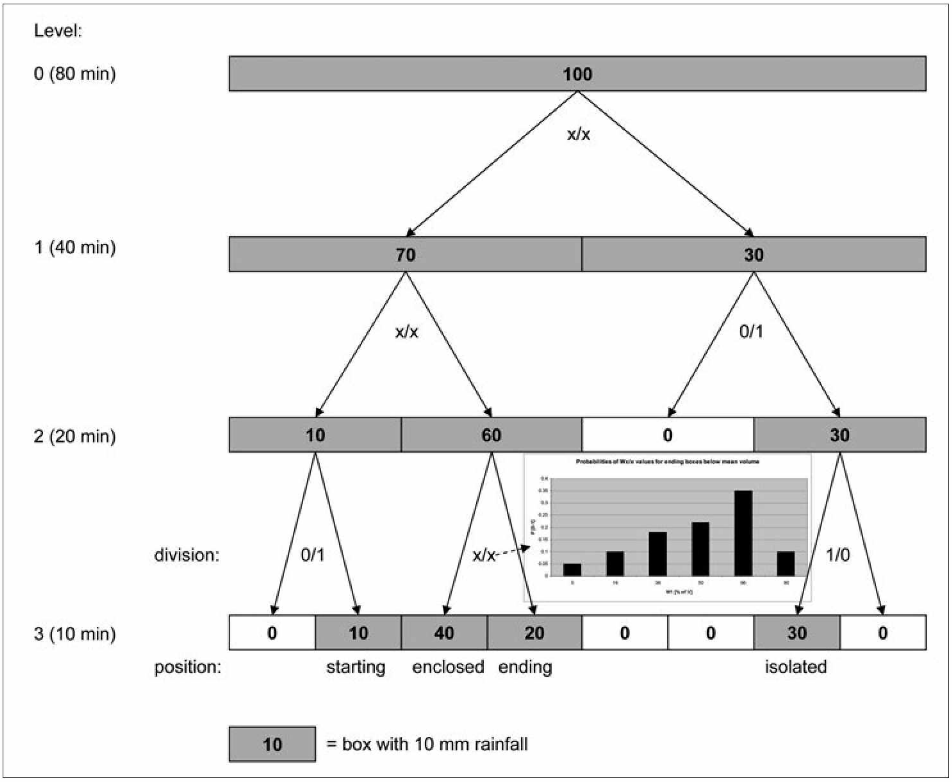

Figure 2: Scheme of the cascade process used in disaggregation.

structure. These are then used to disaggregate low-resolution precipitation data. Prior to disaggregating a time series of rainfall, statistics about the rainfall structure have to be collected, which form a *generator* for the disaggregation procedure. Figure 2 shows the basic aggregation and disaggregation process. The *boxes* in figure 2 denoted from level 0 to 3 represent precipitation volumes at different temporal resolutions. Level 3 consists of measured data with the highest temporal resolution, whereas level 0 defines the resolution, which shall be disaggregated. At each *modulation*, i.e. the transition from one cascade level to the next higher one, the temporal resolution is doubled and the corresponding rainfall volumes are summed up. This process is repeated until the desired resolution has been reached and at each modulation step the following properties are noted to build the generator (terminology is illustrated in figure 2):

- the position of the box within the event: starting, enclosed, ending, isolated;
- the volume of the box: above mean, below mean (at each resolution);
- the division of the box: 0/1-division (whole precipitation occurs in the second half), 1/0-division (whole rainfall volume is in the first half), x/x-division (volumes are split in both boxes)

The resulting statistics of the generator express the probability of a box with known position and volume to be *branched* in a 0/1-division, 1/0-division or x/x-division into two boxes of the lower level. The generator is thus defined as:

$$W_1, W_2 = \begin{cases} 0 \text{ and } 1, \text{ with probability } P(0/1) \\ 1 \text{ and } 0, \text{ with probability } P(1/0) \\ W_{x/x} \text{ and } 1 - W_{x/x}, \text{ with probability } P(x/x) \end{cases} \quad (1)$$

where $0 < W_{x/x} < 1$ and $P(0/1) + P(1/0) + P(x/x) = 1$. The weights are used to assign the volumes $V_1 = W_1 * V$ and $V_2 = W_2 * V$ arising from a branching of a box with volume V. In case of x/x-divisions volume classes are defined additionally and corresponding relative frequencies, i.e. probabilities, are calculated.

For building the generator, scale invariance has to be fulfilled, i.e. the probabilities P and probability distributions W have to be approximately constant over the range of levels to be disaggregated.

After building the generator, disaggregation can be done in the following way:

- determine the position and volume class of a box and look up the corresponding $W_{x/x}$-probabilities;
- generate a random number, assign it to the probability look up table and receive the associated weights to split the volume up in two boxes;
- repeat these steps for each box and each level.

2.2 Data regionalisation

A detailed description of the DANUBIA test site can be found in Mauser & Muerth (2007). Relevant characteristics in the context of this paper are a high gradient in relief from 4,049 m a.s.l to 287 m a.s.l. leading to different synoptic conditions and a high spatial variability in precipitation. Annual precipitation ranges from approximately 650 to 2,000 mm. Governing processes in the formation of rainfall events are, depending on the region, either more convective or advective. The Upper Danube Basin can be divided into three geographical regions with different precipitation regimes as figure 3 shows:

- forelands: maximum of precipitation in summer induced by convective processes;
- low mountain ranges and surrounding areas: two nearly equal maxima in summer and winter, caused by convection and advection;
- alpine regions: very high maximum in summer but also influenced by orographic lift.

Table 1 summarises three rainfall stations, which will be used to regionalise the disaggregation of rainfall.

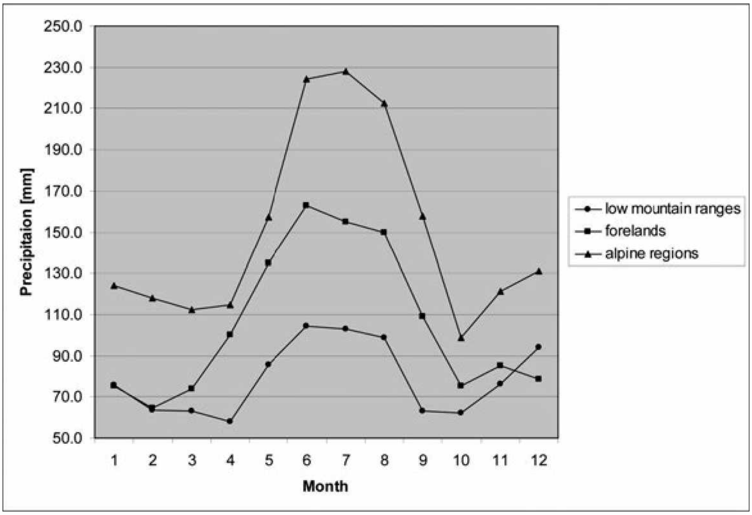

Figure 3: Precipitaion regimes of the different regions in the Upper Danube Basin.

Table 1: Characteristics of the stations used for disaggregation.

Name of station	Wettlkam	Kringell	Untersberg
Latitude	47°54'46" N	48°40'52" N	47°43'23" N
Longitude	11°38'55" E	13°29'35" E	13°03'08" E
Altitude [m a.s.l.]	675	460	1,776
Mean annual precipitation [mm]	1,100–1,400	900–1,000	approx. 1,900
Time period	01/95–12/05 (excl. 97)	12/00–12/05	01/98–07/04
Resolution [min]	10	10	30

2.3 Model application

To apply the model in the desired context some adaptations have been made. As mainly storm events are important for erosion, the boundary of below and above mean volumes was shifted. The new boundary consists of the formula of the German meteorological service (DWD) designating heavy storm events (Baumgartner & Liebscher 1996):

$$P \geq \sqrt{5 \cdot t - \left(\frac{t}{24}\right)^2} \qquad (2)$$

where P is precipitation [mm] and t is duration [min].

Equation 2 was fitted to the RUSLE criterion, where short term rainfall is considered an event, if its maximum 15 minute intensity is greater than 12.5 mm/h (Renard et al. 1996), which results in:

$$P > 0.73 \cdot t^{0.4515} \quad (3)$$

Another reason for substitution of the boundary is, that it is technically not possible to obtain mean volumes at model runtime from the AtmoStations component.

The evaluation of the scale invariance of the generator properties implied that a single generator can be used for station Untersberg. The stations Wettlkam and Kringell do not exhibit scale invariance over all levels, thus two generators (640–160 min, 160–10 min) are used for disaggregation.

Data available from AtmoStations has a 7-, respectively 10-hours resolution hence the disaggregation process has to be validated in a comparable timescale. For stations Wettlkam and Kringell a disaggregation over 7 Levels was chosen (ranging from 10 min to 10.6 hrs) and for Untersberg 5 Levels (ranging from 30 min to 8 hrs) were used. The generator's statistics for disaggregation were built from the whole time periods available (table 1).

3 First results and outlook

For presentation of results, disaggregated precipitation data of 2002 was evaluated. As already mentioned, AtmoStations disaggregates rainfall data into hourly resolution. To receive comparable results between the two disaggregation methods, the disaggregated 10-minutes data was reaggregated to 1 hour. Further on, events were formed from the one hour intervals, for purposes of a simplified, event-based analysis and interpretation. A sequence of successive rainfall volumes is considered an event under the following two conditions:

- minimum duration > 30 min
- minimum volume > 0.2 mm

If a dry period between two events is shorter than 4 hours, the two events are aggregated to a single event. To interpret results in the context of erosion, rainfall erosivities (R) have been calculated via the maximum 60 minute rainfall intensity (EI_{60}) as described in Renard et al. (1996). Comparing the EI_{60} values (table 2) of the two applied methods, one can see, that the AtmoStations disaggregation produces much lower erosivities.

Results in table 2 show a better overall performance of the cascade method. Mean event duration of the AtmoStations method is much too high as a result from the implicit distribution of rainfall over the whole interval of a *Mannheimer Stunde*. This is also the reason for the underestimation of the number of events. The cascade model tends to do the opposite, and produces a larger number of events with a lower mean duration. Similar problems have also been discovered by Güntner et al (2001) and will be subject in subsequent research.

Table 2: Comparison of measured and disaggregated events (1: measured, 2: cascade method, 3: AtmoStations method).

Station	**Wettlkam**			**Kringell**			**Untersberg**		
Method	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
mean evt duration [h]	12.5	10.1	27.6	11.1	11.1	26.5	14.7	12.9	29.7
no of evts	141	179	102	140	154	102	139	167	102
mean of evt maxima	3.12	3.36	1.07	2.99	3.53	1.53	3.02	3.90	1.53
median of evt maxima	1.60	1.96	0.74	1.45	1.90	1.03	2.20	2.69	1.03
mean of evt means	0.77	0.97	0.43	0.91	1.13	0.65	0.96	1.40	0.65
median of evt means	0.55	0.65	0.32	0.55	0.62	0.52	0.73	0.83	0.52
sum of R	1507	1381	465	1539	1765	500	2335	3423	1185

Table 3: RMSE values of maxima, means and erosivity sums of all disaggregated events (2: cascade method, 3: AtmoStations method).

Station	**Wettlkam**		**Kringell**		**Untersberg**	
Method	**2**	**3**	**2**	**3**	**2**	**3**
maxima	4.31	4.50	3.40	4.13	3.40	5.79
means	1.20	0.97	1.57	1.21	1.72	2.01
R sums	27.31	25.90	20.83	25.40	19.40	94.67

Weakest performance of the RMSE values of all events (table 3) for the AtmoStations method are found in Alpine regions, whereas the cascade model seems to produce consistent results over all stations examined. This confirms the concept of regionalisation of the generator properties. As only a validation of the generator against the data used to build itself was made in this paper, the next step will be the regionalisation of the generators with more input data of additional stations. After a second validation of the generators, the above-mentioned geographical regions with different precipitation regimes will be delineated within the GIS-layer of DANUBIA. This will permit the temporal precipitation disaggregtion to be spatially interpolated over the whole test site, thereby allowing the erosion model to gain high-resolution precipitation data from the AtmoStations component.

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